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# THE ATMOSPHERES OF M DWARFS: OBSERVATIONS

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## INTRODUCTION: THE SOLAR/ STELLAR CONNECTION

Until recently, many astrophysicists have viewed the Sun as a special object separated from the stellar context. This situation has arisen mainly because solar research has benefited from high spatial, spectral, and time-resolved observations which were and, for the most part, are unreachable in the observations of ordinary stars. In fact, owing to their enormous distances, only global properties of stars can usually be obtained.

Indeed, especially before the recent opening of the new spectral domains that have been made available by spaceborne instrumentation, solar astrophysicists were regarded by their stellar colleagues as privileged people who were actually able to "see" what they were observing and interpreting. Stellar astronomers could only speculate on the surface characteristics of stars on the basis of indirect and sometimes only rather circumstantial evidence. Solar and stellar research were following increasingly diverging paths because the detailed studies of the Sun, that, usually unintentionally, built up a conceptual division between the study of solar microphenomena and of stellar global characteristics.

I do not know about the authenticity of the following sentence that pictorically reflects the mood of those days: "Solar people are probably watching the Sun too extensively and with excessively powerful instruments, like those looking at an old master painting with a microscope: they might learn a lot about painting techniques but will certainly have a hard time in trying to appreciate the value of the work of art standing in front of them."

As a matter of fact, the astronomical literature and history offer eloquent counterexamples promoting "the investigation of the Sun as a typical star in connection with the study of stellar evolution," as George E. Hale first put it in 1905 (cf. Goldberg, 1983). Nevertheless, for several decades afterwards, Hale's attitude toward what we now call the *solar/stellar connection* did not become astronomical mass culture, in spite of additional positive inputs of several leading scientists such as Eberhard, Schwarzschild, Kron, Unsold, Struve, Schatzman, and Lovell. It was not until the sixties that systematic observations of so-called "active" stars began and the problem of solar-type stellar activity was specifically addressed (cf. Schatzman,1967; Godoli, 1968, and references therein). It is of some significance that the first IAU-sponsored interdisciplinary meetings on topics related to the solar/stellar connection took place only in 1982 (Byrne and Rodonò, 1983; Stenflo, 1983).

From the observational point of view, as both solar and stellar astronomers have constantly increased their respective instrumental capability, leaving almost unchanged the dividing gap between them. Nor will this situation change in the future, as the relative location of the Sun and the stars with respect to the Earth will remain unchanged, with all the obvious implications that differentiate solar and stellar observational capability.

What has definitely changed in the recent past is the attitude of both solar and stellar astrophysicists (as envisaged by Hale long before): the solar/stellar or stellar/solar connection has opened the *solar laboratory*, in which "stellar" phenomena can be studied in detail, to stellar astrophysics and the *stellar laboratory*, where "solar" phenomena occur in different physical environments, to solar astrophysics. A truly "two-way street" connecting solar and stellar research does not appear to be any more an elite culture and is waiting to be fully exploited in the near future.

As always, improvements bring with them an increase of the parameters to be taken into account. Specifically, a new temporal parameter, the stellar evolution time scale, will enter our problem, as well as the other global parameters specifying the physical state of the star's environment.

Recent observations and interpretation of M dwarfs, about 1000 times fainter and 10 times smaller than the Sun, have shown how scientifically fruitful their comparative study could be. Indeed, the intrinsic faintness of M dwarfs and the favorable interior physical conditions for solar-type phenomena to develop render their observation particularly suitable for solar/stellar studies. Therefore, my contribution is aimed at presenting recent observations of M dwarf atmospheres, with particular emphasis on those that relate to the stellar/solar connection (i.e., at the other side—or, perhaps, the "far" (stellar) side—of the topic with respect to the content of *The Sun as a Star* volume in this CNRS-NASA Monograph Series on Nonthermal Phenomena in Stellar Atmospheres.

M dwarf atmospheres, whose theoretical aspects are presented by D. J. Mullan in Chapter 10 of this book, are particularly useful for the purpose of establishing observational constraints on stellar activity parameters. These constraints will greatly help in narrowing the range of possible mechanisms that can give rise to the activity phenomena observed in the Sun and stars. It goes without saying that activity phenomena often announce departure from static thermodynamic equilibrium with particular nonthermal processes dominating others.

After presenting global properties of M dwarfs (*Global Properties of Quiescent M Dwarfs*), I will concentrate on the principal diagnostic of activity phenomena occurring in their atmosphere from the geometrical, energetic, and temporal points of view. Observations of starspots, plages, flares, and activity cycles will be presented in the section *Activity Signatures*. In the final section, the major sources of activity will be discussed with particular emphasis on the generation, intensification, and measurements of stellar magnetic fields.

## GLOBAL PROPERTIES OF QUIESCENT M DWARFS

The intrinsic faintness of M dwarfs makes them suitable for accurate observations only within a relatively restricted volume centered on the Sun. Actually, reasonably detailed photometric and spectroscopic observations have been carried out only for M dwarfs lying within 25 parsecs of the Sun. Nevertheless, since the number density of dM stars is impressively large—0.06 parsecs$^{-3}$ (Thé and Staller, 1974)—a sufficiently numerous sample is available for observations in the solar neighborhood. Basically, there are two distinct groups of M dwarfs: dM and dMe stars, the latter showing hydrogen Balmer lines in emission. (See the section *Effective Temperature, Radius, and Surface Gravity.*) Long-term variability and short-duration flares characterize dMe stars. (See the section *Activity Signatures.*) However, sporadic or quasi-periodic variability seems to be a common feature of a large fraction of M stars (Stokes, 1971).

Extensive and detailed works have been carried out on dMe flare stars. Their global properties are similar to those of ordinary M dwarfs and are of interest here because of the great variety of nonthermal phenomena occurring in their atmospheres.

### Multiplicity and Mass

About 35 percent of late-type main-sequence stars and 60 percent of known flare stars within 25 parsecs of the Sun are members of binary systems (Rodonò, 1978). The majority are visual binaries with well-determined orbits. V 1396 Cyg (Gliese 815 A) and BY Dra (Gliese 719) are spectroscopic binaries, CM Dra (Gliese 630.1) and YY Gem (Gliese 278c) also show eclipses. The most reliable values of masses for well-studied binaries are given in Table 9-1. They range between 0.06 and 0.62 solar masses. Using empirical mass-luminosity relations (viz. Gatewood, 1976) additional determinations of masses are possible. (See the section *Effective Temperature, Radius, and Surface Gravity.*) The smallest value is 0.038 $M_{\odot}$ (V 1298 Aql = Gliese 752 B). However, stars with such low masses cannot be regarded as true main-sequence stars because their contraction times toward the main sequence are comparable to, or even exceed, the age of the Galaxy.

The theoretical models by Grossman et al. (1974) indicate that an increasing fraction of the stellar interior becomes convectively unstable as mass decreases. A star of about 0.2 $M_{\odot}$ or less (i.e., with spectral type later than M5) is already fully convective. Following Mullan

**Table 9-1**
**Masses of dMe Flare Stars in Binary Systems**

| Gliese (1969) No. | Variable Star Name | Catalog | Spectral Type | Binary Type* | $M_A + M_B$ (Sun = 1) | Ref.† |
|---|---|---|---|---|---|---|
| 473 AB | FL Vir | Wolf 424 AB | dM5.5e + dM5e | VB | 0.067 + 0.064 | 1 |
| 234 AB | V 577 Mon | Ross 614 AB | dM4.5(A + B) | VB | 0.114 + 0.062 | 2 |
| | | | | | 0.12 + 0.06 | 3 |
| 65 AB | UV Cet | L726-8 AB | dM5.5e + dM6e | VB | 0.12 + 0.108 | 4, 5 |
| 447 | FI Vir | Ross 128 | dM5 | VB | 0.15 | 6, 7 |
| 860 AB | DO Cep | Kruger 60 B | dM4.5e | VB | 0.16 | 8, 6 |
| 166 C | — | 40 Eri C | dM4e | VB | 0.16 | 9 |
| 630.1 | CM Dra | LP101 - 15/16 | dM4e + dM4e | EB, SB | 0.238 + 0.207 | 10 |
| 15 AB | GQ And | Groom 34 AB | dM1e + dM6e | VB | 0.29 + 0.15 | 6 |
| 815 A | V 1396 Cyg | AC + 30 1214 - 608 | dM3e + ? | SB | 0.2 + 0.3 + ? | 11 |
| 22 | — | BD + 66 34 AA′ | dM2.5e + ? | AB | (0.4) + 0.13 | 6, 12 |
| 799 AB | AT Mic | LDS 720 BC | dM4e + dM4e | VB | 0.39 + 0.30 | 13 |
| 725 AB | — | BD + 59 1915 AB | dM4 + dM5 | VB | 0.41 + 0,41 | 14 |
| 644 | V 1054 Oph | BD - 8 4352 AB | dM3.5e (A + B) | VB | 0.46 + 0.45 | 6 |
| 719 | BY Dra | HDE 234677 | dM0e + dM0e | SB | 0.58 + 0.60 | 15 |
| 278 C | YY Gem | BD + 32 1582 | dM1 + dM1 | EB, SB | 0.62 + 0.57 | 16 |

*Binary type: AB = astrometric, EB = eclipsing, SB = spectroscopic, VB = visual.

†References: 1. Heintz (1972), 2. Lippincott and Hershey (1972), 3. Probst (1977), 4. Worley and Behall (1973), 5. Harrington and Behall (1973), 6. Gatewood (1976), 7. Lippincott (1978), 8. Lippincott (1953), 9. Heintz (1974), 10. Lacy (1977a), 11. Fekel et al. (1978), 12. van de Kamp (1968), 13. De Freitas Mourão (1976), 14. van de Kamp (1971), 15. Bopp and Evans (1973), 16. Leung and Schneider (1978).

(1976), it is tempting to relate the onset of complete convection with the appearance of hydrogen emission lines in almost all dwarfs with spectral type later than M5.

The high fraction of active M dwarfs in binary systems seems to be linked to their ability in preventing rotational breaking with age, a consequence of forced synchronization between rotation and orbital motion (Bopp and Fekel, 1977; Bopp and Espenak, 1977). Rather than duplicity, their higher than normal rotational velocity and deep convection zones appear to be necessary conditions for activity phenomena to develop in late-type stars. On the other hand, that enhanced activity results from triggering effects due to their proximity is not supported by the present observations of flare events in binaries (Rodonò, 1978).

### Galactic Density, Motion, and Age

M dwarfs account for about 73 percent of all main-sequence stars in the solar neighborhood or about 66 percent of the total number of stars in our Galaxy (Allen, 1973; Arakelian, 1969). Hence, as the histograms in Figure 9-1 show, although their individual masses are very low (bottom panel), their huge number (middle panel) makes them the largest single contributors to the stellar mass of our Galaxy. Assuming that the mass and space distribution of neighborhood stars are representative of the entire Galaxy, the upper panel in Figure 9-1 shows that M dwarfs account for about 50 percent of the total mass of main-sequence stars.

From the relative abundance of dMe and dM stars versus the absolute magnitude given by Joy and Abt (1974) and the luminosity function in Allen (1973), the number of dMe is about 75 percent of dM stars (i.e., they have a number density in the solar neighborhood of about 0.04 stars $pc^{-3}$). Hence, assuming: (1) all dMe to be flare stars, (2) the density in the solar neighborhood to be representative for the entire Galaxy, and (3) a conventional volume of the Galaxy of $10^{12}$ $pc^3$, the number of flare stars amounts to the impressive number $3.8 \times 10^{10}$ stars. An even higher estimation is given

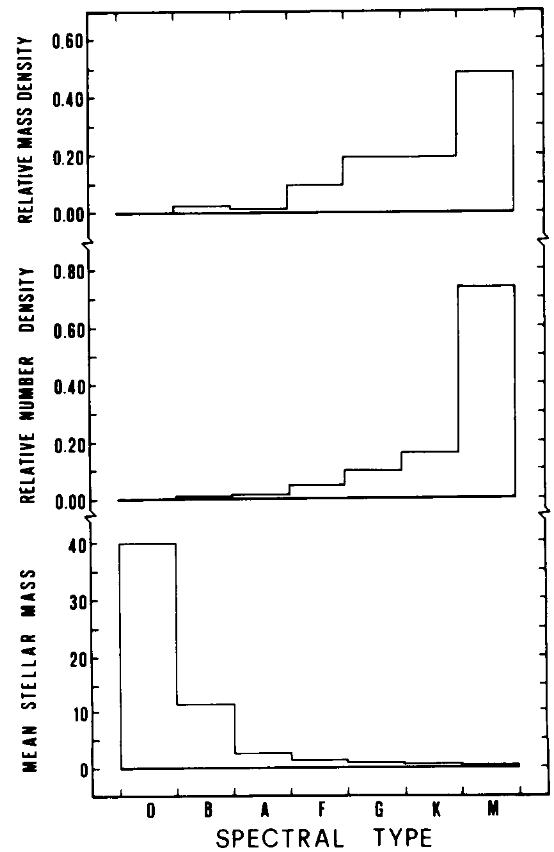


*Figure 9-1. Distribution of mean mass versus spectral type for main-sequence stars (bottom histogram), their relative number (middle histogram), and mass density (upper histogram) in the solar neighborhood. Assuming that these distributions are representative of the entire Galaxy, the low-mass M dwarfs appear to be the largest single contributor to the stellar mass in our Galaxy.*

by Coleman and Worden (1976): 1.0 to $8.6 \times 10^{11}$ stars. They have also suggested that a large fraction of stellar mass loss may arise from dMe active stars during the course of flare events with important consequences on the physics and composition of the interstellar medium. (See also Staller, 1976; Gershberg and Shakovskaya, 1976; and Mullan, 1979.) Even assuming our lower estimate of the total number and mass of flare stars, the mass loss due to flares from dMe stars might constitute an important fraction of the total mass loss from stars, especially if a quasi-steady solar-type wind is also present.

The mass density of M dwarfs is 0.025 $M_\odot$ $pc^{-3}$ (Allen, 1973), accounting for about 19 percent of the total mass of our Galaxy as given by Oort from z velocity (Allen, 1973). Therefore, dMe flare stars alone constitute a sizable mass component of the Galaxy ($\sim$15 percent).

The relative maximum in the luminosity function at about $M_V$ = 15 (Luyten, 1968; Arakelian, 1969) is almost entirely due to emission-line dwarfs. This leads Arakelian (1969) to suggest the existence of a relatively young group of physically related stars in the solar neighborhood. Moreover, since dMe stars have lower dispersion velocity and higher vertex deviation than dM stars (Einasto, 1954, 1955; Vyssotsky and Dyer, 1957; Gliese, 1958), flare stars have been generally considered young objects. However, Greenstein and Arp (1969) first detected flare activity on a kinematically old star (Wolf 359 = CN Leo). Moreover, considering the space motions of the 22 flare stars which were known at that time, Lippincott (1971) found their mean velocity (21 km $s^{-1}$) to be comparable to the average (23 km $s^{-1}$) for 202 M dwarfs in the Gliese (1969) catalog. Hence, Lippincott (1971) questioned the younger age of flare stars relative to other M dwarfs.

On the other hand, Chugainov (1972) and Kunkel (1972) gave evidence for the existence of both young and old flare stars and for higher activity levels on younger stars. Recent investigations on the space motions of 646 red dwarfs (Shakhovskaya, 1975) have confirmed that the most active UV Cet type variable stars are indeed young; however, less active stars belong to the old disk population and at least one case is known (CF UMa = Gliese 451B) with both kinematic and chemical (Tomkin, 1972) halo population characteristics. In addition, the short-period spectroscopic and eclipsing binary system, CM Dra (Gliese 630.1), which shows a light curve distortion outside eclipses attributable to starspots such as for BY Dra, has Population II kinematical motion (Lacy, 1977a).

Other examples of old flare stars are presented by Veeder (1974a), who found 14 of 31 single or double flare stars to have space motions typical of old disk population. Updating his flare list, 18 of 38 single or double flare stars included in Veeder's (1974b) list of M dwarfs have old disk motions. This high fraction of old flare stars (47 percent) can be biased by observational selection since most of them originally came from lists of large proper motion stars. Actually, Iwanowska (1972) has found that only about 13 percent of dM and 11 percent of dMe stars belong to Population II. The relatively large fraction of old stars in Lippincott's (1971) flare star sample can explain her negative result on the younger age of flare stars relative to other dM dwarfs. This is certainly true on the average, as demonstrated by the larger number and earlier spectral type of flare stars in young clusters and associations and by their rather strong emission lines, which are an index of youth as suggested by Wilson (1963) and demonstrated by Wielen (1974) and Upgren (1978).

The existence of old flare stars is not completely consistent with the widespread idea on the fading of flare activity with age. For instance, the suggestion that the dMe or the flare star, which forms a binary system with another dM, is always the less evolved member has not been confirmed. Several brighter components of such systems do show flare activity (see Rodonò, 1978). The most recently reported case is that of Gliese 867A (Byrne, 1979; Butler et al., 1981). Moreover, contrary to previous evidence, Veeder (1974a) has shown that, in the $M_{bol}$-($V$-$K$) diagram, some UV Cet type flare stars lie below the main sequence by as much as one magnitude.

In conclusion, although youth can be considered a sufficient condition for low-mass stars to show flare activity, the existing evidence also suggests that some mechanism, such as enforced rotation in binary systems, is capable of prolonging considerably the active phase on a large fraction of stars.

### Effective Temperature, Radius, and Surface Gravity

The most reliable values of surface gravity are those obtained from the radii and masses of the spectroscopic and eclipsing binaries, CM Dra (Lacy, 1977a) and YY Gem (Bopp, 1974a; Leung and Schneider, 1978). We must rely on indirect methods for additional data.

Pettersen (1983a) has critically reviewed the existing data on global properties of active M dwarfs in their quiescent state. The resulting empirical relations involving effective temperature ($T_e$), bolometric correction (BC), absolute visual magnitude ($M_v$), and color indices $B$-$V$, $V$-$R$, $R$-$I$, and $V$-$K$ are presented in Table 9-2. Given the well-defined correlation between $T_e$ and $V$-$K$, the HR diagram ($M_{bol}$ versus log $T_e$) in Figure 9-2 has been calibrated to show the $M_{bol}$ versus $V$-$K$ correlation also.

Since well-observed dM stars are very near the Sun, their trigonometric parallaxes are quite reliable, and absolute visual magnitudes can be determined. Hence, by using the bolometric correction (Gatewood, 1976) or the bolometric magnitude and the effective temperature derived from their spectral energy distribution (Veeder, 1974a), masses and radii can be computed. Assuming the mass-luminosity relation and the effective temperature/($V$-$K$) color relation given by Veeder (1974b), we have:

$$\log R/R_\odot = 0.92 - 0.20\, M_{bol} + 0.104\,(V\text{-}K) \quad . \tag{9-1}$$

Another method of determining stellar radii has been adopted by Lacy (1977b). He has estimated the radii of nearby stars with known distance using the Barnes-Evans relation (Barnes and Evans, 1976; Barnes et al., 1976):

$$F_v = A - B\,(V\text{-}R)_0 \quad , \tag{9-2}$$

where $A$ and $B$ are constant within given ranges of the $V$-$R$ color index. The quantity $F_v$ is the so-called "visual surface brightness parameter," which is related to the stellar surface flux, and is given by the relation,

$$F_v = 4.2207 - 0.1\, V_o - 0.5 \log \phi' \quad , \tag{9-3}$$

**Table 9-2**
**Empirical Correlations Between Global Parameters of M Dwarfs from Various Sources (see text)**

| | |
|---|---|
| BC = $-0.379\, M_V + 2.386$ | (±0.27) |
| BC = $-4.816\,(B-V) + 5.430$ | (±0.36) |
| BC = $-2.267\,(V-R) + 1.689$ | (±0.13) |
| BC = $-2.124\,(R-I) + 0.874$ | (±0.13) |
| BC = $-0.816\,(V-K) + 1.709$ | (±0.07) |
| $T_e = -1510\,(B-V) + 5738$ K | (±156) |
| $T_e = -645\,(V-R) + 4469$ K | (±112) |
| $T_e = -648\,(R-I) + 4311$ K | (± 79) |
| $T_e = -264\,(V-K) + 4624$ K | (±120) |
| $\log (R/R_\odot) = 0.92 - 0.20\, M_{bol} + 0.104\,(V-K)$ | (Eq. (9-1)) |
| $\log (M/M_\odot) = 1.82 - 0.25\, M_{bol}\ (M_{bol} > 7.8)$ | (Eq. (9-6)) |
| $\log (M/M_\odot) = 0.45 - 0.09\, M_{bol}\ (M_{bol} < 7.8)$ | (Eq. (9-7)) |
| $\log T_e = 3.77 - 0.052\,(V-K)$ | (Eq. (9-8)) |

where $V_o$ is the unreddened visual magnitude and $\phi'$ is the stellar angular diameter in milliarcsec. Combining relation (9-3) and the relationship between $\phi'$, the stellar radius ($R$) and distance ($d$), in the form:

$$R/R_\odot = 0.1074 \times (\phi' \text{m-arcsec}) \times d\,(\text{pc}), \quad (9\text{-}4)$$

Lacy (1977b) derived the relation,

$$\log R/R_\odot = 7.4724 - 0.2\, V_o - 2\, F_v\,(V\text{-}R) + \log d\,(\text{pc})\ . \quad (9\text{-}5)$$

This method is a powerful one because it is free from assumptions about spectral classification, luminosity class, effective temperature, and bolometric correction. Its application is particularly useful for statistical purposes. A systematic difference between the radii computed using Equation (9-1) and Veeder's (1974b) data and those computed by Lacy (1977b) is apparent in Figure 9-3. Lacy (1977b) has not considered this difference to be significant. However, because Lacy's data are consistent with independent estimates obtained by Gray (1967, 1968) following an observational/theoretical approach, it would be interesting to check whether the above discrepancy is due to a systematic overestimation of the effective temperature with increasing $M_{bol}$ in the ($V$-$K$) - $T_e$ calibration by Veeder.

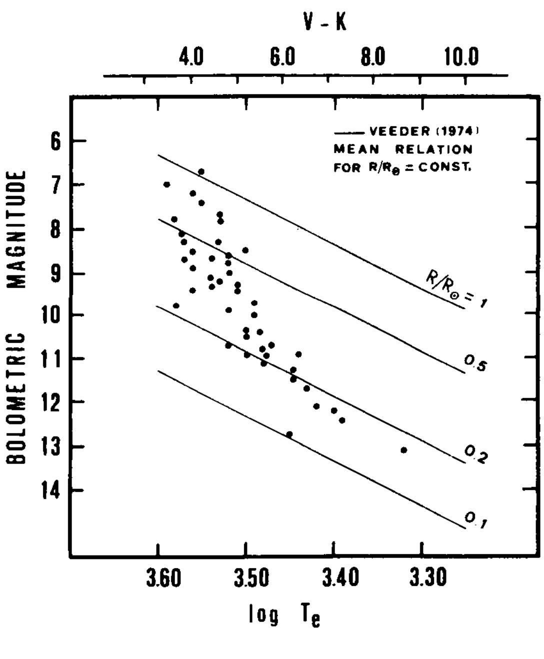


*Figure 9-2. Bolometric magnitude versus effective temperature for M dwarfs. The upper scale (V-K) has been calibrated using Equation (9-8). Continuous lines indicate Veeder's (1974b) relation for constant $R/R_\odot$ values (Eq. (9-1)).*

Lacy (1977b) and Sienkiewicz (1982) have confirmed the result already found by Hoxie (1973) that theoretical radii for the solar composition zero-age main sequence by Copeland et al. (1970) are about 30 to 15 percent smaller than those derived from observations. A systematic overestimation of effective temperature for theoretical models of very late main-sequence stars or inadequate treatment of the opacity sources in their atmospheres can cause these discrepancies.

Bolometric magnitude, $V$-$K$ color, mass, effective temperature, radius, and surface gravity are given in Table 9-3. The bolometric magnitudes and $V$-$K$ colors (Veeder, 1974b), which are given in the first two columns, were used to calculate the remaining parameters by means of the empirical relation (9-1) and the following ones:

$$\log (M/M_o) = 1.82 - 0.25\, M_{bol} \quad (M_{bol} > 7.8)\ , \quad (9\text{-}6)$$

$$\log (M/M_o) = 0.45 - 0.91\, M_{bol} \quad (M_{bol} < 7.8)\ , \quad (9\text{-}7)$$

$$\log T_e = 3.77 - 0.052\,(V\text{-}K)\ . \quad (9\text{-}8)$$

The above relations are from Gatewood (1976), Cester (1965), and Veeder (1974b), respectively. Independently determined more recent data (e.g., the masses and the $T_e$ values) computed by Veeder (1974b) by fitting a blackbody curve to broadband magnitudes, which

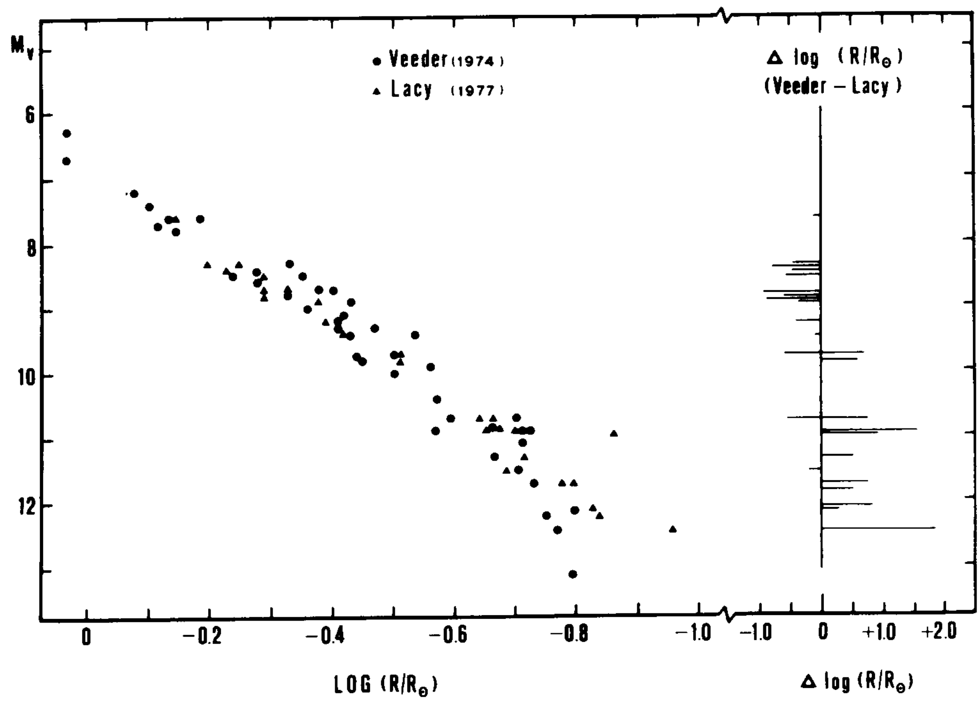


*Figure 9-3. Absolute visual magnitude versus log (R/R ⊙) for M dwarfs. The comparison between the radii computed using Equation (9-1) and Veeder's (1974b) data and those given by Lacy (1977b) shows a systematically increasing deviation, which is probably due to a systematic overestimation of the effective temperature in the (V-K) - $T_e$ calibration by Veeder.*

are listed in Table 9-1, are preceded by the symbol, Λ. The surface gravity, $g/g_{\odot}$ was computed from the values of mass and radius given in Table 9-1.

The radius of well-studied dMe stars ranges from about 1 $R_{\odot}$ for CR Dra (Gliese 612.2) and FF And (Gliese 29.1) to 0.16 $R_{\odot}$ for UV Cet (Gliese 65B), G 51-15, and V 1298 Aql (Gliese 752B); the surface gravity ranges from less than the solar value for CR Dra to 5.2 $g_{\odot}$ for Gliese 725B; and the effective temperature ranges from 3800 K for the primary component of YY Gem (Gliese 278C) to 2100 K for V 1298 Aql. For the two components of the spectroscopic binary YY Gem, Leung and Schneider (1978) give 3806 ± 182 and 3742 ± 214 K, respectively. Given the listed values of mass and radius, the mean density of dM stars is higher, up to more than 20 times, than the solar value. V 1298 Agl (Gliese 752B) is the faintest and coolest dM star which is known.

## Quiescent Optical Spectra and Abundances

As already noted at the beginning of this chapter, the global characteristics of dM and dMe stars are similar. Due to their low temperature (2100 to 3800 K), the optical spectra are dominated by strong molecular bands of TiO (4590, 4630, 4670, 4810, 5010, 5175, 5450, 5850, and 6520 Å) and of CaOH (5500 to 5560 Å blended with the TiO band at 5450 Å). The most intense absorption line is due to CaI at 4226 Å. In addition, other faint absorption features due to CO, OH, MgH (4845, 5210, and 5620 Å), CrI (between 4200 and 4300 Å), and CaH (6389 Å) are usually visible in low dispersion spectra (100 to 200 Å $mm^{-1}$).

**Table 9-3**

**Bolometric Magnitude ($M_{bol}$), $V$–$K$ Color, Mass ($M/M_\odot$), Effective Temperature ($T_e$), Radius ($R/R_\odot$), and Surface Gravity ($g/g_\odot$) for UV Cet and BY Dra-Type Dwarfs**

| Gliese No. | Variable Star Name | Spectral Type | $M_{bol}$ | $V$–$K$ | $M/M_\odot$ | log $T_e$ | $R/R_\odot$ | $g/g_\odot$ | Notes* |
|---|---|---|---|---|---|---|---|---|---|
| 15 A | GQ And a | M2.5e V | 8.9 | 4.0 | Λ0.29 | 3.56 | 0.36 | 2.24 | – |
| 15 B | GQ And b | M4.5e V | 10.9 | 5.1 | Λ0.15 | Λ3.498 | 0.19 | 4.16 | – |
| 29.1 | FF And | dM0e | 7.2 | 4.1 | 0.62 | 3.56 | 0.81 | 0.94 | SB |
| 48 | – | dM3.5e | 8.3 | 4.0 | 0.56 | Λ3.532 | 0.55 | 1.85 | – |
| 51 | V 358 Cas | dM7e | 10.7 | 6.0 | 0.14 | Λ3.470 | 0.25 | 2.24 | – |
| 65 A | UV Cet a | dM6e | 11.7 | 6.6 | Λ0.12 | Λ3.431 | 0.18 | 3.70 | – |
| 65 B | UV Cet b | dM4e | 12.1 | 6.7 | Λ0.11 | 3.42 | 0.16 | 4.30 | – |
| 83.1 | TX Ari | dM5e | 11.1 | 5.6 | 0.11 | 3.48 | 0.19 | 3.05 | – |
| 109 | – | dM4e | 9.2 | 4.6 | 0.33 | 3.53 | 0.36 | 2.55 | – |
| 207.1 | V 371 Ori | dM3e | 8.6 | 4.9 | 0.47 | 3.52 | 0.51 | 1.81 | – |
| 234 A | V 577 Mon | dM4e | 10.4 | 5.6 | Λ0.12 | Λ3.484 | 0.26 | 1.78 | VC |
| 268 | – | dM5e | 9.8 | 5.6 | 0.23 | 3.58 | 0.35 | 1.89 | – |
| 277 A | – | dM3e | 7.7 | 4.7 | 0.56 | 3.53 | 0.74 | 1.02 | SB |
| 277 B | – | dM4.5e | 8.5 | 5.1 | 0.50 | 3.50 | 0.56 | 1.59 | – |
| 278 C1 | YY Gem a | M1e V | 7.8 | 3.8 | Λ0.62 | Λ3.580 | Λ0.66 | 1.42 | EB |
| 278 C2 | YY Gem b | M4.5e V | 8.1 | 3.8 | Λ0.57 | Λ3.573 | Λ0.58 | 1.69 | EB |
| 285 | YZ CMi | dM4.5e | 9.7 | 5.5 | 0.25 | Λ3.491 | 0.36 | 1.93 | – |
| – | G51–15 | dMe | 12.4 | 7.6 | 0.05 | Λ3.389 | 0.17 | 1.73 | – |
| 388 | AD Leo | M4.5e V | 8.8 | 4.8 | 0.42 | 3.52 | 0.46 | 1.98 | – |
| 406 | CN Leo | dM6e | 12.2 | 7.4 | 0.06 | Λ3.398 | 0.18 | 1.85 | – |
| 412 B | WX UMa | dM5e | 12.7 | 6.1 | 0.04 | 3.45 | 0.10 | 4.00 | – |
| 424 | SZ UMa | M1 V | 8.3 | 3.8 | 0.56 | 3.57 | 0.45 | 2.77 | – |
| 447 | FI Vir | dM5 | 10.8 | 5.5 | Λ0.15 | 3.48 | 0.21 | 3.40 | – |
| 473 AB | FL Vir | dM5.5e | 11.5 | 6.4 | Λ0.07 | Λ3.447 | 0.19 | 1.94 | MC |
| 494 | DT Vir | dM2e | 7.4 | 4.2 | 0.60 | 3.55 | 0.75 | 1.07 | – |
| 516 A | VW Com | dM4e | 9.1 | 4.5 | 0.35 | 3.54 | 0.37 | 2.56 | – |
| 526 | – | M4e V | 8.5 | 4.0 | 0.50 | 3.56 | 0.43 | 2.70 | – |
| 551 | V 645 Cen | dM5e | 11.7 | 6.6 | 0.08 | Λ3.431 | 0.18 | 2.47 | – |
| 616.2 | CR Dra | M1e | 6.7 | 4.2 | 0.69 | 3.55 | 1.04 | 0.64 | – |
| 630.1A | CM Dra a | M4e | 10.4 | – | Λ0.24 | Λ3.498 | Λ0.25 | Λ3.48 | EB |
| 630.1B | CM Dra b | – | 10.5 | – | Λ0.21 | Λ3.498 | Λ0.23 | Λ3.97 | EB |
| 644 AB | V 1054 Oph | dM4.5e | 8.7 | 4.6 | Λ0.46 | Λ3.538 | 0.46 | 2.17 | MC |
| 669 A | V 639 Her a | dM4e | 9.0 | 4.9 | 0.37 | Λ3.518 | 0.43 | 2.00 | – |
| 669 B | V 639 Her b | dM5e | 10.0 | 5.5 | 0.21 | Λ3.491 | 0.31 | 2.19 | – |
| 719 | BY Dra | M0e V | 7.0 | 3.4 | Λ0.60 | 3.59 | 0.75 | 1.07 | SB |
| 725 A | – | dM4 | 9.3 | 4.4 | Λ0.41 | Λ3.538 | 0.33 | 3.76 | – |
| 725 B | – | dM5 | 9.9 | 4.7 | Λ0.41 | Λ3.519 | 0.27 | 5.62 | – |
| 729 | V 1216 Sgr | dM4.5e | 10.9 | 5.2 | 0.12 | Λ3.477 | 0.19 | 3.32 | – |
| 735 | V 1285 Aql | M2e | 7.8 | 4.6 | 0.55 | 3.53 | 0.69 | 1.16 | – |
| 752 B | V 1298 Aql | dM3.5e V | 13.1 | 8.7 | 0.04 | 3.32 | 0.16 | 1.56 | – |
| 781 | – | dM3e | 9.4 | 4.0 | 0.30 | 3.56 | 0.29 | 3.57 | SB |
| 860 B | DO Cep | dM4.5e | 10.7 | 4.9 | Λ0.16 | 3.52 | 0.19 | 4.43 | – |
| 866 | – | dM6e | 10.9 | 6.6 | 0.12 | Λ3.439 | 0.27 | 1.65 | – |
| 867 B | – | dM4e | 9.3 | 5.0 | 0.31 | 3.51 | 0.38 | 2.15 | – |
| 873 | EV Lac | dM4.5e | 9.4 | 5.0 | 0.30 | 3.51 | 0.36 | 2.31 | – |
| 905 | – | dM6e | 11.3 | 6.4 | 0.10 | Λ3.447 | 0.21 | 2.27 | – |
| 908 | – | M2e V | 8.7 | 3.9 | 0.44 | 3.57 | 0.39 | 2.89 | – |

*Notes: EB = eclipsing binary component; MC = mean component of visual double; SB = mean component of spectroscopic binary; VC = corrected for visual companion; Λ = parameter obtained independently, not from empirical relations (see text).

For temperatures lower than 3500 K, $H_2O$ rotational lines appear. The relation of molecular line strength to effective temperature is shown in Figure 9-4 from Pettersen (1983a). For further detail, refer to the standard dM star spectra by Abt et al. (1968) and Keenan and McNeil (1976).

Another common feature of dM and dMe spectra is the occurrence of chromospheric Ca II H and K resonance lines in emission, which characterize all dwarf stars with spectral types cooler than F5 (Wilson, 1973; Linsky et al., 1979; Giampapa et al., 1981; Linsky et al., 1982).

The spectral feature that differentiates dMe from dM stars is the hydrogen Hα emission line (Joy and Abt, 1974). Most dMe stars also show other emission lines, such as the higher Balmer lines up to H8–9, the He I (5876 and 6678 Å) and Na D lines (5890 to 5896 Å) (Giampapa et al., 1978; Worden et al., 1981).

A distinctive characteristic of Hα and other higher Balmer lines in emission is the central reversal that is apparent in spectra with resolution of the order of 0.1 Å (Kulapova and Shakhovskaya, 1973; Worden and Peterson, 1976; Pettersen and Coleman, 1981; Worden et al., 1981; Linsky et al., 1982). Repeated observations of the same star, although nonsystematic, clearly show that this feature is variable. Hα reversal does not appear in the spectra of dMe spectroscopic binaries, probably because it is smeared by rotational broadening.

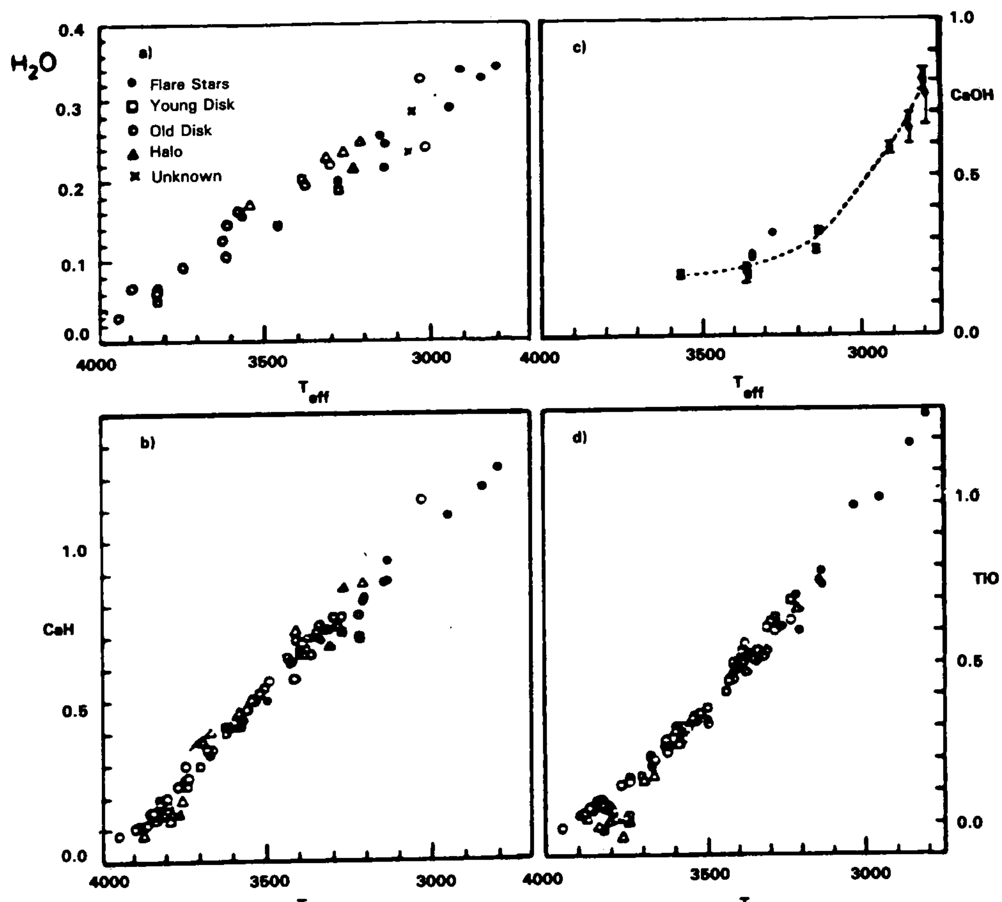


*Figure 9-4. Empirical correlations between effective temperature and strengths of molecular features in red-dwarf stars (from Pettersen, 1983a).*

Several interpretations of H$\alpha$ reversal are possible. However, following Worden and Peterson (1976) and Worden et al. (1981), optically thick emitting regions in the H$\alpha$ emission-line core—similar to solar active regions such as plages, spicules, and prominences—seem to be likely candidates. A selection of line profiles of Ca II H and K, H$\alpha$, and Na D is presented in Figures 9-5, 9-6, and 9-7.

From comparative study of high-resolution Ca II H and K lines in dM and dK5–Me stars, Giampapa et al. (1981) have shown that surface fluxes and radiation temperatures are systematically higher in the latter. They have also confirmed that, for both emission and nonemission dwarfs, the ratio of surface flux in the H and K lines to the bolometric one, $R_{HK} = [F' (H_1) = F' (K_1)]/(\sigma T_e)$, is comparable to or larger than that for supergiants and definitely larger than that for giants (Blanco et al., 1974; Linsky et al., 1979).

The fraction of dMe stars among all M dwarfs increases with advancing spectral subclass to nearly 100 percent at M5. However, Liebert et al. (1979) and Giampapa (1983a) have found several non-emission-line stars among M dwarfs with $M_v > 15$. The occurrence of such emission lines in only a fraction of late K and M dwarfs indicates that different outer atmospheric regimes can be set up in stars that have similar global physical properties. In emission-line dwarfs, excess nonradiative energy deposition leads to chromospheric temperature gradients steeper than in non-emission-line dwarfs so that, as shown by Kelch et al. (1979) and Cram and Mullan (1979), Balmer lines develop emission cores. They have found that successful modeling of Balmer-line absorption in dwarfs also requires some degree of nonradiative chromospheric heating. A solar analogy is particularly useful in this context in predicting a possible origin for the enhanced chromospheric emissions. As shown by Shine and Linsky (1974), Basri et al. (1979), and Vernazza et al. (1981), the strong emission lines from solar chromospheric plages require temperature or pressure gradients steeper than those of adjacent quiescent regions.

Since solar plages are characterized by enhanced magnetic flux, nonradiative heating in closed magnetic structures is likely to produce the required steep temperature gradient and the observed enhanced emission. This analogy suggests that dMe star chromospheric structures are dominated by closed magnetic fields. Some debate has occurred on how the magnetic fields might be generated (cf. Worden, 1974; Mullan, 1975a). This topic will be discussed at some length in the section *Nonthermal Energy Sources of Activity and Conclusions*, together with other indirect evidence and actual measurements of magnetic field strength in dMe stars. (See also the section *Activity Signatures*.) Here, it is worth mentioning that a self-excited $\alpha$–$\omega$ dynamo in the convection zone appears to be the basic mechanism for magnetic field production in active stars (cf. Belvedere, 1983). The interaction of convection and rotation leads to a regime of differential rotation, which is required by the dynamo mechanism. Since dM and dMe stars have comparable masses and the theoretical models indicate that they are highly convective, the parameter that triggers emission-line characteristics and activity should be the higher than normal rotational velocity of dMe stars with respect to M stars. The high incidence of late K–M emission-line active stars in close binary systems, in which synchronization between orbital motion and rotation enforces high stellar rotation, is consistent with the foregoing scenario of magnetic field generation.

In Table 9-4, typical parameters for emission lines in late K–M dwarfs and the observed range of variability are presented. In fact, one must bear in mind that sporadic variability of the emission-line intensity frequently occurs. From the very beginning of systematic spectroscopy of dMe flare stars at the Crimea and McDonald Observatories, independent evidence of sporadic emission-line variability on time scales of the order of 1 hour, other than during flare events, was collected (cf. Gershberg, 1977). Even a transient, almost complete gradual disappearance of H I and Ca II emission lines has been observed on YZ CMi (Bopp,

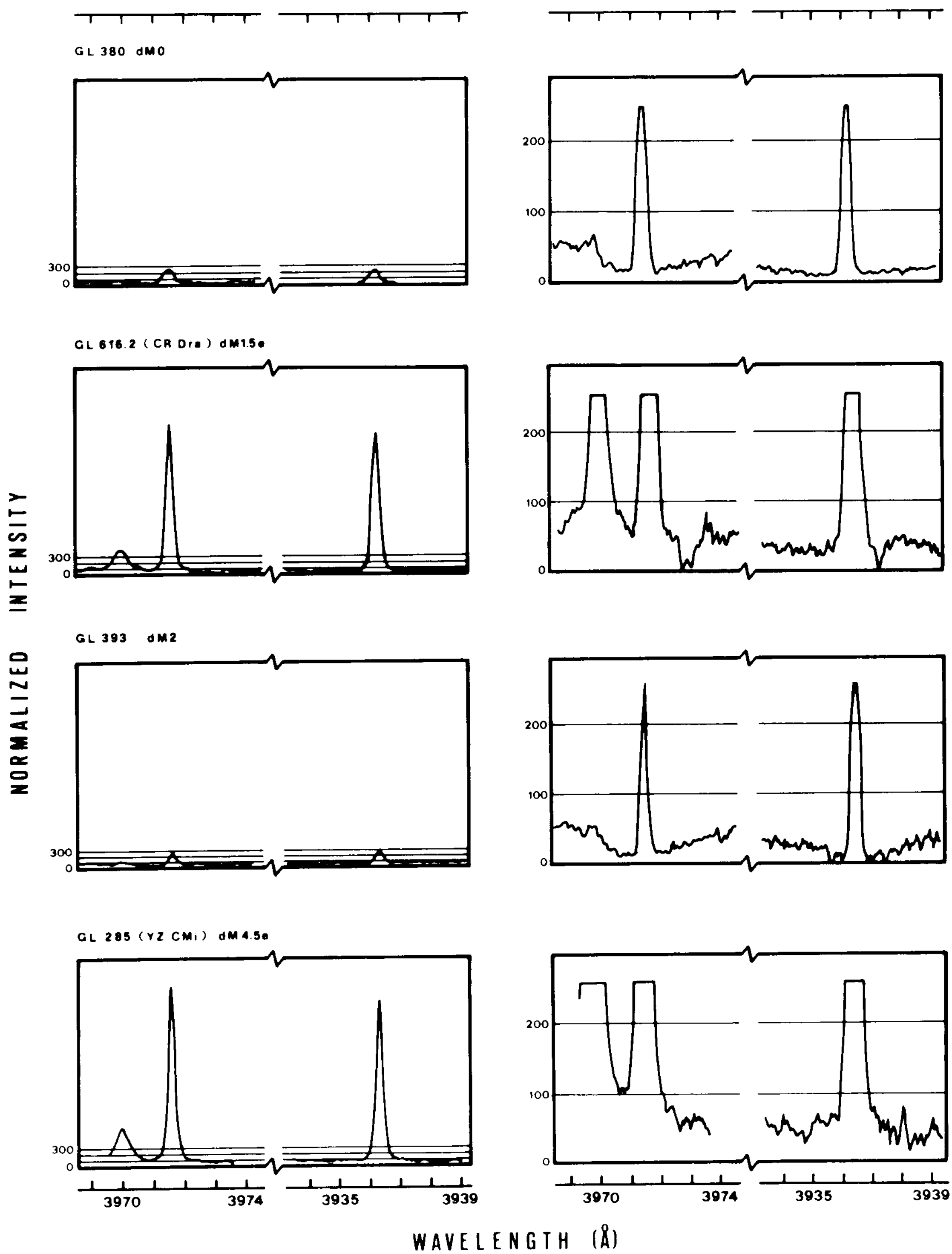


*Figure 9-5. High-resolution Ca II H and K line profiles in dM and dMe stars (from Giampapa et al., 1981). The vertical axes are scaled so that 100 corresponds to the maximum surface flux between the H and K lines. Each star is plotted twice on two different scales (left and right panels). The vertical scales on the right panels have been enlarged with respect to those on the left for the same star to show the line core profiles.*

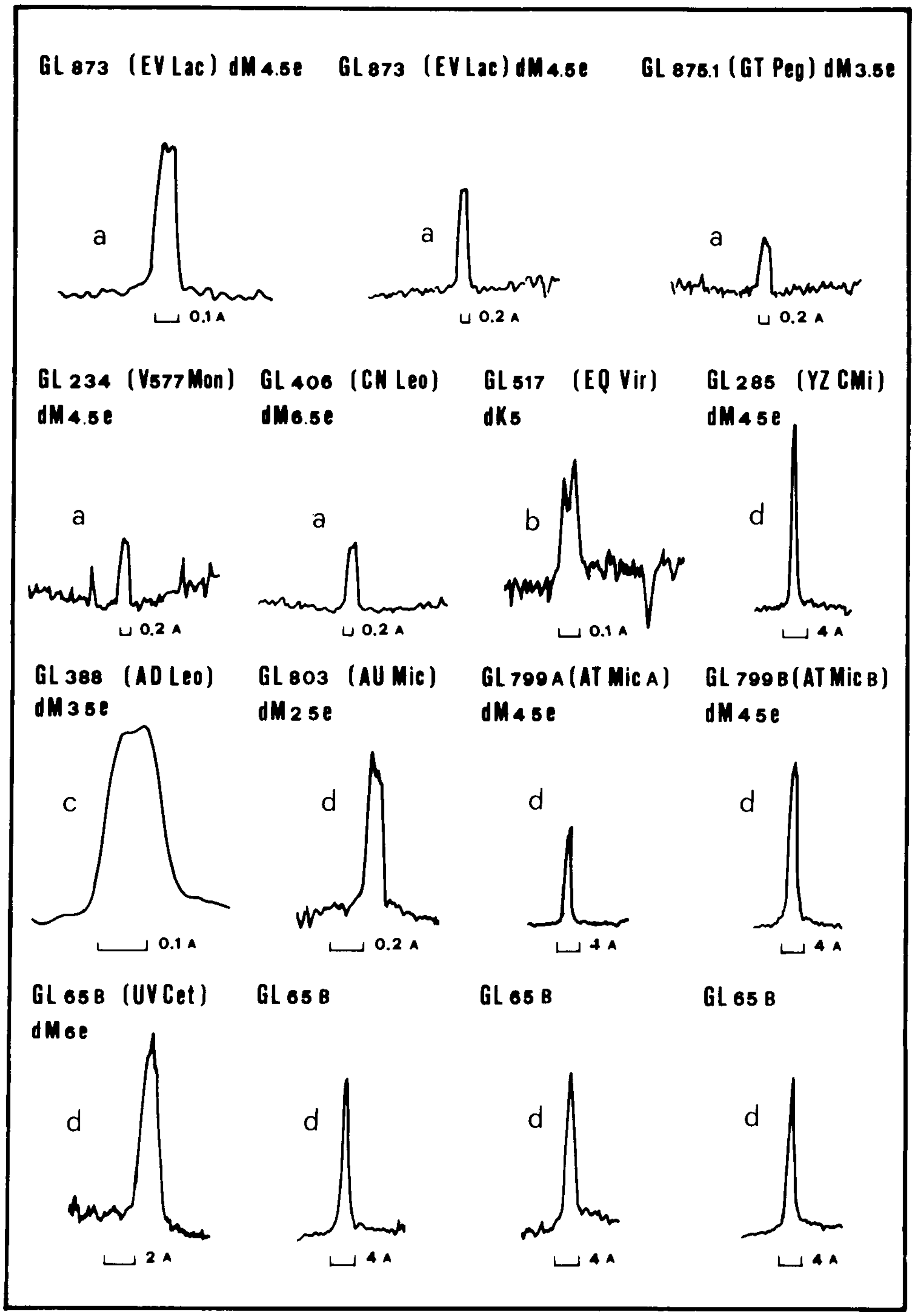


*Figure 9-6. High-resolution neutral hydrogen Hα line profiles from various sources. Repeated observations of the same star have shown that the Hα central reversal, which probably arises from solar-type optically thick active regions, is a variable spectral feature. From (a) Worden and Peterson (1976), (b) Hartmann and Anderson (1977), (c) Giampapa et al. (1978), and (d) Linsky et al. (1982).*

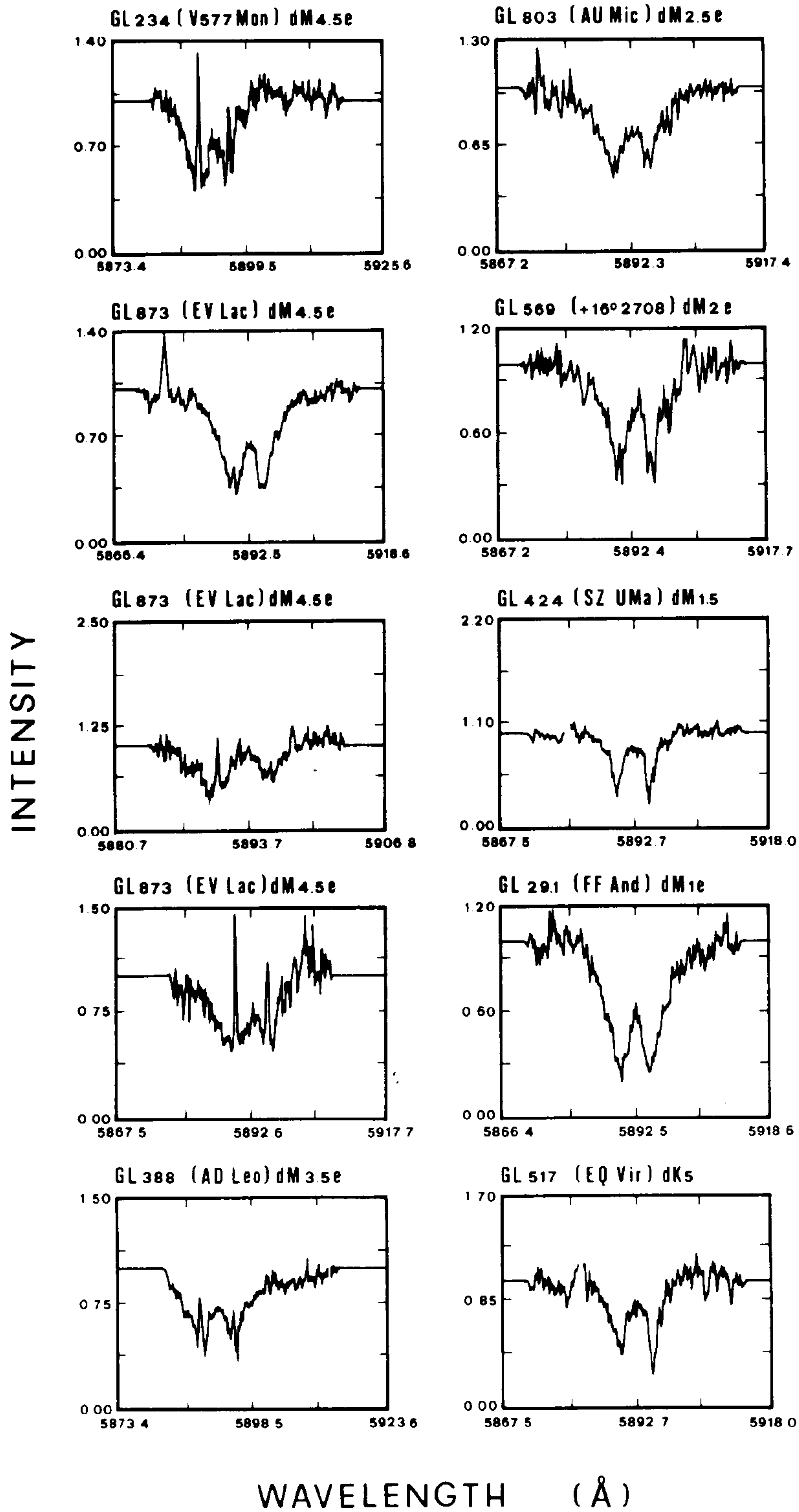


*Figure 9-7. High-resolution profiles of Na D lines in M dwarfs (from Worden et al., 1981).*

## Table 9-4

**Surface Flux ($F$) in the Principal Ultraviolet Emission Lines for the Sun and Active Late-Type K–M Dwarfs and Assumed Ratio of Surface Flux to Observed Flux at Earth ($F/f_\oplus$)**

| Star (spectral type) | $T_e$ | $F/f_\oplus$ | λ(A): 1240 Ion: NV $T_{max}$(K:) 2(5) | 1304 O I, S I 9(3)? (fluor) | 1335 C II 2(4) | 1400 b1 Si IV, O IV 8.3(4) | 1549 C IV 1.3(5) | 1640 He II 2(4)? (recomb) | 1657 C I 6.(3) | 1812 b1 Si II, S I 6.5(3) | 2610 b1 Fe II | 2800 b1 Mg II 6.5(3) | 3960 + 3990 Ca II H+K 6.(3) | 6563 H I (H α – Hk) 6.(3) | Ref.† |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Quiet Sun (G2V) | 5770 | – | 6.4(2)(a)* | 5.6(3) | 6.7(3) | 3.6(3) | 6.6(3) | 1.2(3) | 8.4(3) | 2.4(4) | abs. | 1.3(6) | 5.0(5) | – | 1 |
| Solar Active Region | – | – | 5.8(3) | 2.2(4) | 3.0(4) | 1.5(4) | 2.9(4) | 1.9(4) | 1.7(4) | 5.0(4) | – | – | – | – | 2 |
| Solar Very Act. Region | – | – | 8.1(3) | 3.0(4) | 4.7(4) | 2.1(4) | 2.6(4) | 2.7(4) | 2.4(4) | 7.4(4) | – | – | – | – | 2 |
| α Cen B (K1V) | 5225 | 4.02(15) | 8. (2) | 5.3(3) | 5.0(3) | 3.4(3) | 6.4(3) | 8. (2) | – | 2.0(4) | – | 9.5(5) | – | – | 3 |
| II Peg–Quiet (K2V) | (4700) | 3.52(17) | 1.4(4) | 1.2(5) | 1.4(5) | 3.5(4) | 2.7(5) | 1.9(5) | 1.4(5) | 1.4(5) | – | 3.1(6) | | – | 4 |
| II Peg–Plage | (4700) | | 1.2(5) | 3.9(5) | 5.6(5) | 5.1(5) | 1.6(6) | 5.0(5) | 4.5(5) | 3.3(5) | – | 4.4(6) | | – | 4 |
| ϵ Eri (K2V) | 5010 | 3.25(16) | 5.9(3) | 1.8(4) | 2.2(4) | 1.1(4) | 3.3(4) | 1.8(4) | 1.6(4) | 6.4(4) | – | 2.4(6) | 1.5(6) | – | 3 |
| ϵ Ind (K5V) | 4400 | 4.22(16) | – | 4.4(3) | 5.5(3) | – | <1.9(3) | – | 5.3(3) | 1.4(4) | – | 5.9(5) | – | – | 5 |
| EQ Vir (dK5e) | 4400 | 1.50(18) | 8.1(4) | <3 (4) | 1.2(5) | ~1.1(5) | 1.4(5) | ~1.2(5) | 4.8(4) | ~7.5(4) | 2.4 | 2.0(6) | 1.9(6) | – | 1 |
| 61 Cyg B(K7V) | 4130 | 4.31(16) | 1.2(3) | 2.1(3) | 1.4(3) | – | 3.5(3) | 9.1(2) | 2.4(3) | 6.9(3) | 1.2(5) | 2.7(5) | 1.2(5) | – | 1 |
| HD 88230 (K7V) | 4100 | 5.87(16) | – | 5.0(3) | 6.5(3) | – | 3.5(3) | 1.8(3) | ~5. (3) | 8.8(3) | 2.0(4) | >5.1(5) | 1.3(5) | – | 1 |
| HD 1326A (M1.3V) | 3780 | 1.37(17) | 1.5(4) | – | <5. (3) | – | <7. (3) | – | 3.2(3) | 1.0(4) | – | 5.5(5) | – | – | 1 |
| AU Mic (M1.6eV) | 3730 | 2.17(17) | 3.5(4) | 4.1(4) | 4.8(4) | ~5. (4) | 1.3(5) | 6.3(4) | 5.2(4) | 5.2(4) | 6.7(5) | 8.9(5) | 1.5(6) | 4.5(6) | 1 |
| | | | 4.1(4) | 2.6(4) | 3.7(4) | | 6.2(4) | 6.5(4) | | 1.3(4) | 1.7(5) | 5.6(5) | – | – | 6 |
| AU Mic – Quiet | – | – | 1.4(4) | 2.8(4) | 2.6(4) | 1.1(4) | 5.6(4) | 2.8(4) | 2.0(4) | 2.2(4) | 2.8(5) | 5.6(5) | – | – | 4 |
| – Plage | – | – | 1.6(4) | 2.4(4) | 4.0(4) | 2.6(4) | 9.6(4) | 5.4(4) | 2.1(4) | 3.7(4) | 3.0(5) | 8.0(5) | – | – | 4 |
| – Flare | – | – | 3.0(4) | – | 3.9(4) | 2.2(4) | 1.2(4) | 5.0(4) | 2.4(4) | 3.1(4) | – | – | – | – | 7 |
| HD 95735 (M1.0V) | 3720 | 5.88(16) | – | 1.3(3) | <1. (3) | – | <2. (3) | 5. (3)? | <3. (3) | 4.7(3) | 2.1(4) | 4.6(4) | 1.1(4) | – | 1 |
| EQ Peg A (M3.5eV)(b)* B (M4.5eV) | 3510 | 2.88(17) | 2.1(4) | 2.0(4) | 5.5(4) | 3.2(4) | 1.1(5) | 2.7(4) | 2.9(4) | 3.5(4) | – | – | – | – | 1 |
| AT Mic A (M4.5eV) B (M4.5eV) | 3430 | 2.73(17) | 2.0(4) | 4.1(4) | 6.6(4) | 3.5(4) | 1.7(5) | 4.6(4) | 3.8(4) | 5.5(4) | 3.5(5) | 3.9(5) | – | – | 1 |
| EV Lac (M4.5eV) | 3430 | 3.05(17) | – | – | – | – | – | – | – | – | – | – | 6.9(5) | 5.2(5) | 1 |
| YZ CMi (M4.3eV) | 3380 | 6.60(17) | 8.6(4) | 1.1(4) | 7.3(4) | ~2.4(4) | 1.8(5) | 3.6(4) | 9.2(4) | 5.0(4) | 4.8(5) | 8.6(5) | 5.5(5) | 3.9(6) | 1 |
| V 645 Cen (M5.5eV) (Prox Cen) | 3200 | 1.16(16) | 9 (3) | 6 (3) | 1.0(4) | – | 1.9(4) | 6. (3) | – | 6. (3) | – | 1.0(5) | – | – | 1 |
| UV Cet (M6e V+M6eV) | 3200 | 2.80(17) | 1.4(4) | 1.2(4) | 1.7(4) | 1.8(4) | 5.9(4) | 1.0(4) | 1.8(4) | 1.1(4) | 7.3(4) | 1.4(5) | 6.7(4) | 2.4(6) | 1 |

*Notes: (a) 6.4(2) = $6.4 \times 10^2$, (b) computed from observed fluxes by Hartmann et al. (1982) and $F/f_\oplus$ ratio (= $2.88 \times 10^{17}$) by Linsky et al. (1982).

†Reference: 1. Linsky et al. (1982), 2. quoted by Hartmann et al. (1979a), 3. Ayres et al. (1981b), 4. unpublished data from coordinated SERC-NASA-ESA observations with IUE by the Armagh, Boulder, and Catania groups, 5. Hartmann et al. (1982), 6. from observed fluxes by Hartmann et al. (1982) and $F/f_\oplus$. ratio by Linsky et al. (1982), 7. Butler et al. (1981).

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1974b). This type of short-term sporadic variability—if not due to fading flares or rotational modulation of active region visibility—suggests actual transient changes in the physical conditions underlying the emitting region; these are conceivably due to nonthermal instabilities. Baliunas et al. (1981) have also detected periodic variability of the emission cores of Ca II H and K lines in $\epsilon$ Eri (K2 V) similar to those seen in solar oscillations.

Stellar model chromospheres developed at the Joint Institute for Laboratory Astrophysics by J.L. Linsky and his collaborators in a recent series of papers, most of which are quoted in this section, have corroborated the suggestion first outlined by Gershberg (1970, 1974) about the qualitative similarity of solar and stellar chromospheres. However, the latter are less extended, hotter, denser and show larger surface inhomogeneities than those of the Sun (cf. 3.2). (See the section *Surface Inhomogeneities in the Outer Atmosphere.*)

From the width of hydrogen lines, an upper limit of 14000 K for the chromospheric electron temperature can be predicted. However, the centrally reversed H$\alpha$ profiles have a half-width of $\sim 1$ Å, implying a temperature of $4 \times 10^4$ K for an optically thick emitting region with electron density lower than $10^{13}$ cm$^{-3}$. The intensity ratio of triplet to singlet He I emission lines, I(5876)/I(6678), is 3.7 (i.e., similar to that in active solar prominences). These He I lines are probably excited by collision from ground state in the chromospheric region with $T$ = 2-5 $\times$ $10^5$ K and column density $n_e \times \ell \sim 6 \times 10^{18}$ cm$^{-2}$, implying that the chromospheric regions for $n_e = 10^{10}$ to $10^{12}$ cm$^{-3}$ are thin. Even thinner chromosphere could result if, according to Kunkel (1970) and Gershberg (1974), $n_e$ = $10^{12}$ to $10^{14}$ cm$^{-3}$.

In addition to age, abundance is believed to be responsible for the large spread of M dwarfs in the HR diagram. However, Hartmann and Anderson (1977) did not find appreciable abundance differences between emission and non-emission K7-M1 dwarfs. They made a curve of growth analysis of high-dispersion echelle spectra of six old disk stars obtained at the Kitt Peak 4-meter telescope in the region of 5900 to 6600 Å with 0.1 to 0.15 Å resolution. The derived abundances were similar to the solar ones to 0.2 dex.

From high-resolution Fourier transform infrared (1.5 to 2.5 $\mu$) spectra of six K7-M5 dwarfs and subdwarfs obtained with the same Kitt Peak telescope, Mould (1978) concluded that subdwarfs are metal poor ([M/H] $\simeq$ -0.3), whereas the one star in his sample which was above the main sequence is metal rich ([M/H] = 0.5). He also gave an upper limit of 0.2 magnitude to the dispersion in the HR diagram attributable to abundance effects.

A search for the lithium line at 6707 Å (Bopp, 1974c) in 14 flare stars showed no detectable lithium (EW < 50 mA), but on Gliese 182 = V 1005 Ori (EW ~ 200 mA). De la Reza et al. (1981) have confirmed this detection and obtained a ratio [Li/H] close to the interstellar value.

Essentially, none of the studied late K-M emission-line dwarfs differ from field K-M stars in their lithium content (Herbig, 1965). This is consistent with their highly convective structures, implying severe pre-main-sequence lithium depletion (Bodenheimer, 1965). The only BY Dra flare star with high lithium abundance is the K4 Ve dwarf, BD-10 4662AB (FK Ser). However, it is not clear whether it is in a post T Tauri phase (Herbig, 1973) or, according to its infrared colors, is a low-active T Tauri star (Zappala, 1974). Actually, its infrared excess is one order of magnitude lower than a *bona fide* T Tauri star (Hackwell et al., 1974).

Pettersen (1983a) notes that much caution should be exercised in deriving metal-to-hydrogen ratios for active stars from the photometric metallicity index. As demonstrated by Giampapa et al. (1979) for the solar case, active region photometry in the Strömgren system leads to apparent lower metal abundance than for the quiet Sun. Therefore, photometrically determined metal abundance for dMe stars will be systematically lower than for dM stars because of the integrated effect of their huge active regions with filling factors up to 100 percent.

### Ultraviolet, X-Ray, and Radio Data

The optical spectra of dM and dMe stars show the signatures of powerful solar-type chromospheres (i.e., of atmospheric regions in which the temperature gradient $dT/dh$, which is negative in the photosphere, becomes positive, and nonradiative heating dominates the energy balance). However, the temperature regime of chromospheres (4300 to 25000 K) and of the overlying shallow transition regions (25000 to $1 \times 10^6$ K) and the coronae (1 to $3 \times 10^6$ K), together with the monotonic decrease of matter density, allow the formation of numerous low to high excitation emission lines and continua, which fall into the ultraviolet and X-ray domains. The International Ultraviolet Explorer (IUE) and Einstein satellites, which became operative in 1978, have greatly contributed to the impressive progress in the study of the outer atmospheres, particularly for red-dwarf stars. Their faint or nonexistent ultraviolet background continua make it possible to detect and analyze important spectral features, such as Mg II h and k (2803 and 2796 Å), O I (1305 and 1355 Å), C I (1657 Å), Si II (1808 and 1812 Å), the Fe II multiplet (~2610 Å), Si II (1335 Å), Si III (1892 Å), C III (1175 and 1909 Å) Si IV (1394 and 1403 Å), C IV (1548 and 1551 Å), N V (1238 and 1242 Å), and O V (1371 Å). Soft X-ray emission is essentially ubiquitous among red-dwarfs, with dMe stars having the largest ratios of $L_x/L_{bol}$ (cf. Linsky, 1980a, 1980b; Vaiana, 1981; Vaiana et al., 1981). These are powerful diagnostics for nonradiative heating processes in the outer stellar atmospheres.

A few representative LWR* and SWP† spectra of quiescent dMe stars obtained with IUE are presented in Figures 9-8 and 9-9, respectively.

The recent insight into the physics of red-dwarf atmospheres needs to be viewed in the general context of stellar outer atmospheres. The major observational results include the following:

1. The radiative loss in the Ca II H and K emission lines alone, which accounts for only a fraction of the total chromospheric energy loss in red dwarfs (Linsky et al., 1982), cannot be accounted for by the dissipation of acoustic fluxes based on the Lighthill-Proudman theory (cf. Stein, 1967; Renzini et al., 1977) as first shown by Blanco et al. (1974). Refined calculations by Bohn (1983) now seem to overcome this difficulty also at the coronal level.

2. The Mg II fluxes (Linsky and Ayres, 1978; Basri and Linsky, 1979; Linsky et al., 1982) and the coronal soft X-ray emissions (Vaiana et al., 1981; Ayres et al., 1981b) are independent of gravity and effective temperatures, contrary to what is expected if heating by acoustic-wave dissipation dominates. Slow mode magnetohydrodynamics (MHD) waves in flux tubes have been subsequently proposed to overcome this difficulty (Ulmschneider and Bohn, 1981).

3. A plot of emission-line surface fluxes versus temperature of line formation in quiescent G–M dwarfs shows a qualitative trend similar to that of the quiet Sun, but in M dwarfs, the emission lines are fainter by a factor of 3. Instead, active and dMe star surface fluxes in chromospheric lines are comparable to, or up to one order of magnitude larger than, those of solar very active regions (VAR's). The enhanced emissions in dMe stars get progressively larger than the solar one, up to two orders of magnitude, at higher temperatures of formation (i.e., at transition region and coronal levels (Ayres et al., 1981b; Oranje et al., 1982; Rodonò, 1983; Linsky et al.,

*Long-wavelength redundant (camera).
†Short-wavelength primary (camera).

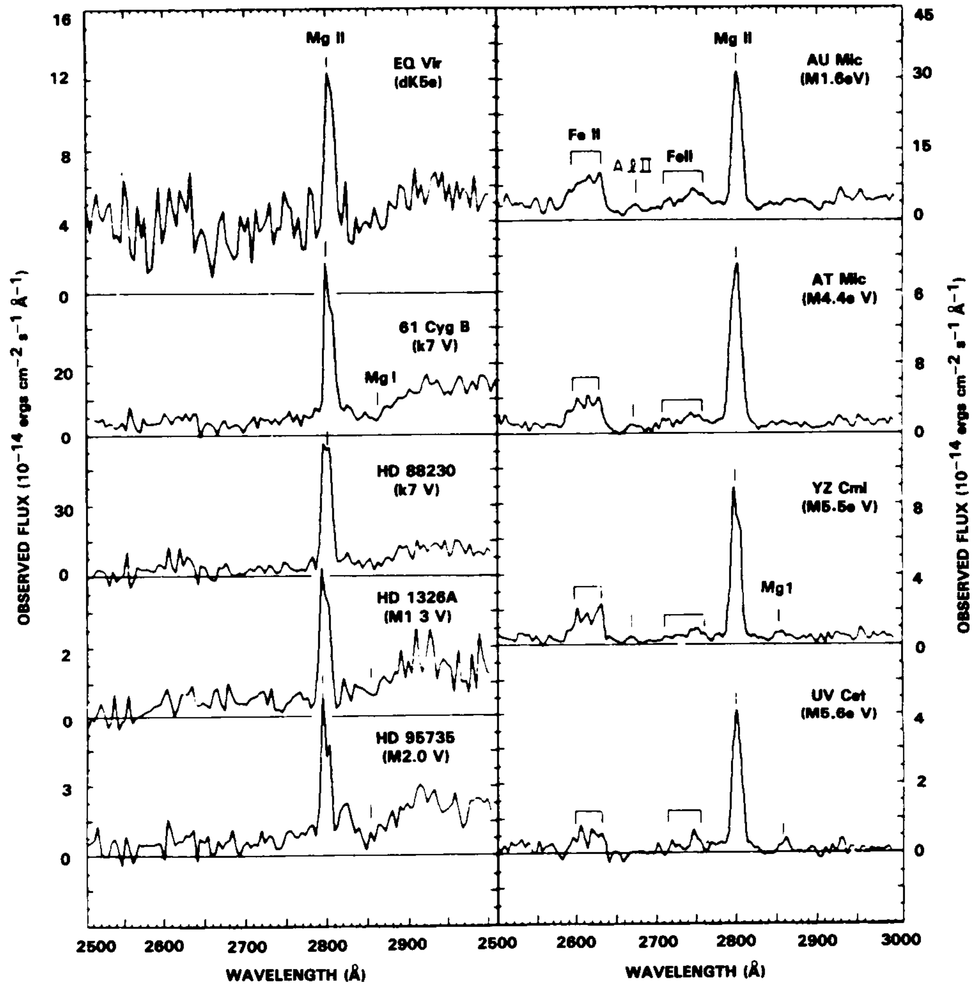


*Figure 9-8. Typical Mg II h and k emission lines and Fe II line blend (2610 Å) in low-resolution ultraviolet spectra of M dwarfs obtained with the LWR (2000 to 3200 Å) camera of IUE. The line flux increases by several units during active phases (from Linsky et al., 1982).*

1982)). A plot of surface fluxes in UV emission lines versus temperature of formation for several representative sources (Figure 9-10) clearly shows that the heating rate of transition regions and coronae is much higher or efficient than at chromospheric levels. The correlation plots in Figure 9-11 between chromospheric, transition region, and coronal flux ratios for cool giants and dwarfs (Ayres et al., 1981a) indicate linear logarithmic correlations, whose slopes increase in passing from chromospheric to coronal diagnostics.

4. Stars with chromosphere-corona transition regions appear to be located in definite areas of the HR diagram (Linsky and Haisch, 1979; Ayres et al., 1981b; Simon et al., 1982), areas in which solar-type hot coronae are observed (F–M dwarfs and late F–K giants), whereas cool stellar winds or hybrid-spectra (Hartmann et al., 1980; Hartmann, 1983) characterize

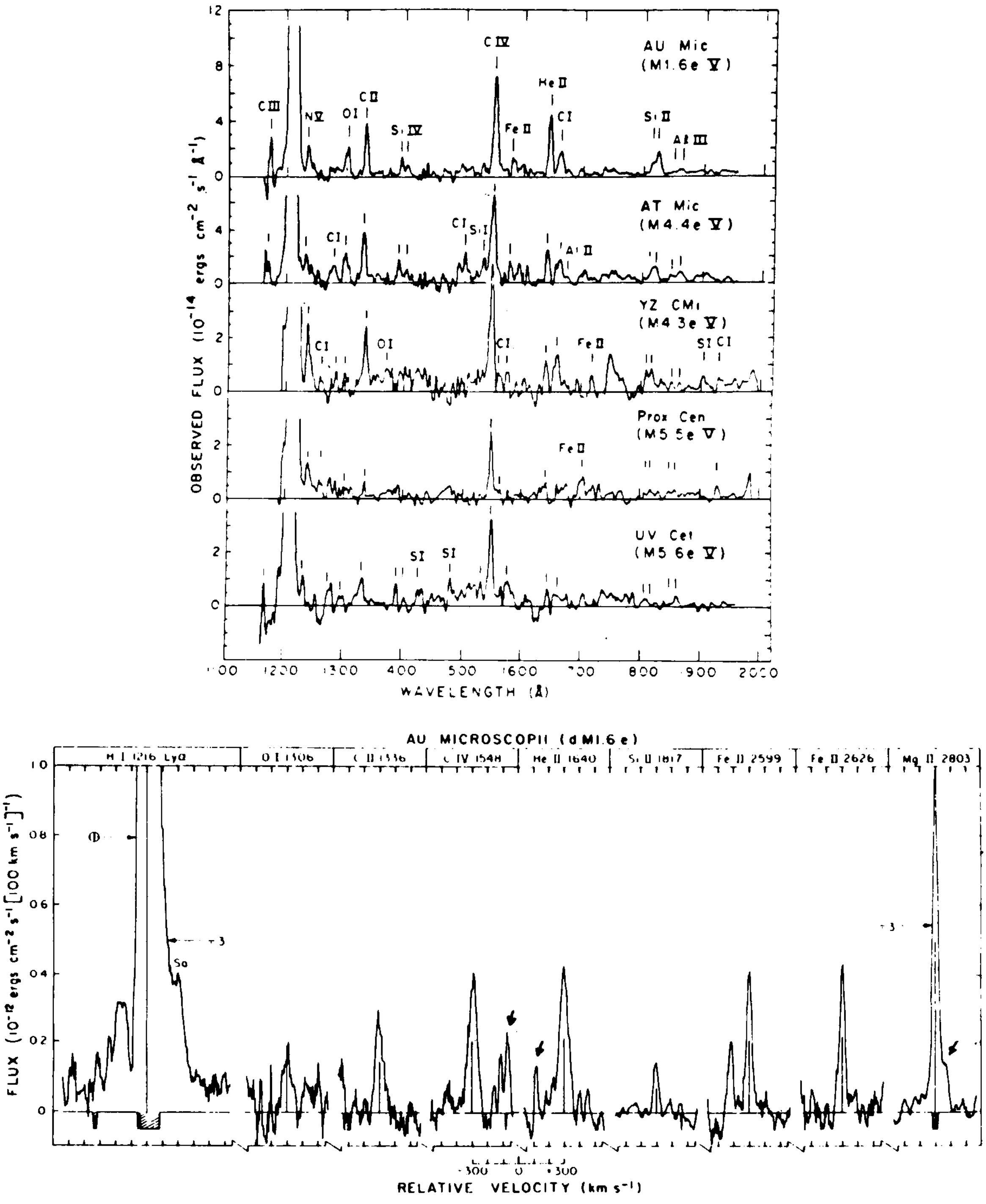


*Figure 9-9. Upper panel: Chromospheric and transition-region emission lines in low-resolution ultraviolet spectra of M dwarfs obtained with the SWP (1150 to 2000 A) camera of IUE (from Linsky et al., 1982). The temperature of line formation ranges from a few thousands (C I, O I) to more than 200000 K (C IV, N V). Lower panel: High-resolution profiles of major UV lines from deeply exposed SWP and LWR spectra of the flare star, AU Mic (M1.5e), obtained by Ayres et al. (1983). The wavelength scale is calibrated in relative velocity. Arrows designate prominent particle radiation events or blemishes (from Ayres et al., 1983).*

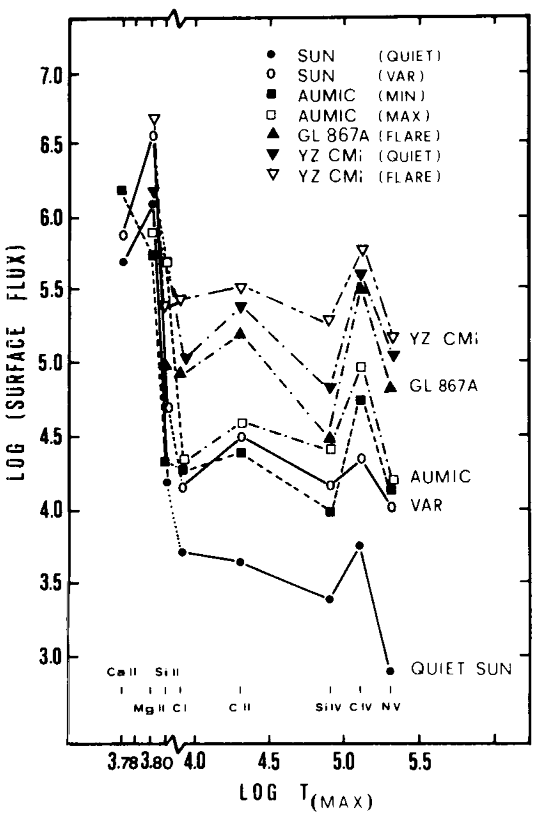


*Figure 9-10. Surface fluxes in UV emission lines versus maximum temperature of formation ($T_{max}$) for M stars at quiescent and active phases compared with the qualitatively similar trends for the quiet Sun and a solar very active region (VAR) (from Rodonò, 1983).*

brighter red giants and supergiants (Stencel, 1978; Stencel and Mullan, 1980; Haisch and Simon, 1982). As suggested by Linsky (1983a, 1983b), among others, what differentiates cool dwarfs with transition regions and hot coronae from supergiants with cool winds is the structure of magnetic fields that dominate in their outer atmospheres; *closed flux tubes* enhance the energy deposition and prevent the outflow of plasma across the field lines, whereas *open magnetic structures* lead to strong stellar winds. The evidence for closed magnetic loops from observed activity phenomena in red dwarfs will be presented in the section *Activity Signatures.* As in the best known active star—the Sun—closed and open magnetic structures may well exist at the same time. What differentiates dMe from dM stars is that, in the former, closed magnetic loops dominate over open structures so that the energy deposition in the outer atmosphere is enhanced, giving rise to surface inhomogeneities like plages. (See the section *Surface Inhomogeneities in the Outer Atmosphere.*) On the other hand, open structures and possibly slow mass loss may dominate in dM stars, making them observationally less remarkable than active dMe stars.

5. The well-known increase of chromospheric radiative losses with rotationl velocity and inverse square root of age (Skulmanich, 1972, and references therein) also apply to chromospheric UV, transition region, and coronal fluxes (Ayres and Linsky, 1980; Pallavicini et al., 1981; Walter, 1982; Golub, 1983, references therein). Several of these functional relations have been critically analyzed by Catalano and Marilli (1983). They conclude that the various empirical relations between chromospheric and coronal diagnostics with stellar rotation and age for main-sequence stars arise because the rotation period depends *only* on stellar mass ($m$) and age ($t$). They found the following exponential correlations:

$$L_K(M/M_\odot, t) \sim L_K(1,0)$$

$$\times\ (M/M_\odot)^{5.1} \times 10^{-1.5 \times 10^5 \sqrt{t}} \quad ,$$

$$L_X \sim L_K^{2.6} \quad .$$

These empirical relations are fundamental for the purpose of establishing firm observational constraints on theories of stellar activity, such as the $\alpha$–$\omega$ dynamo

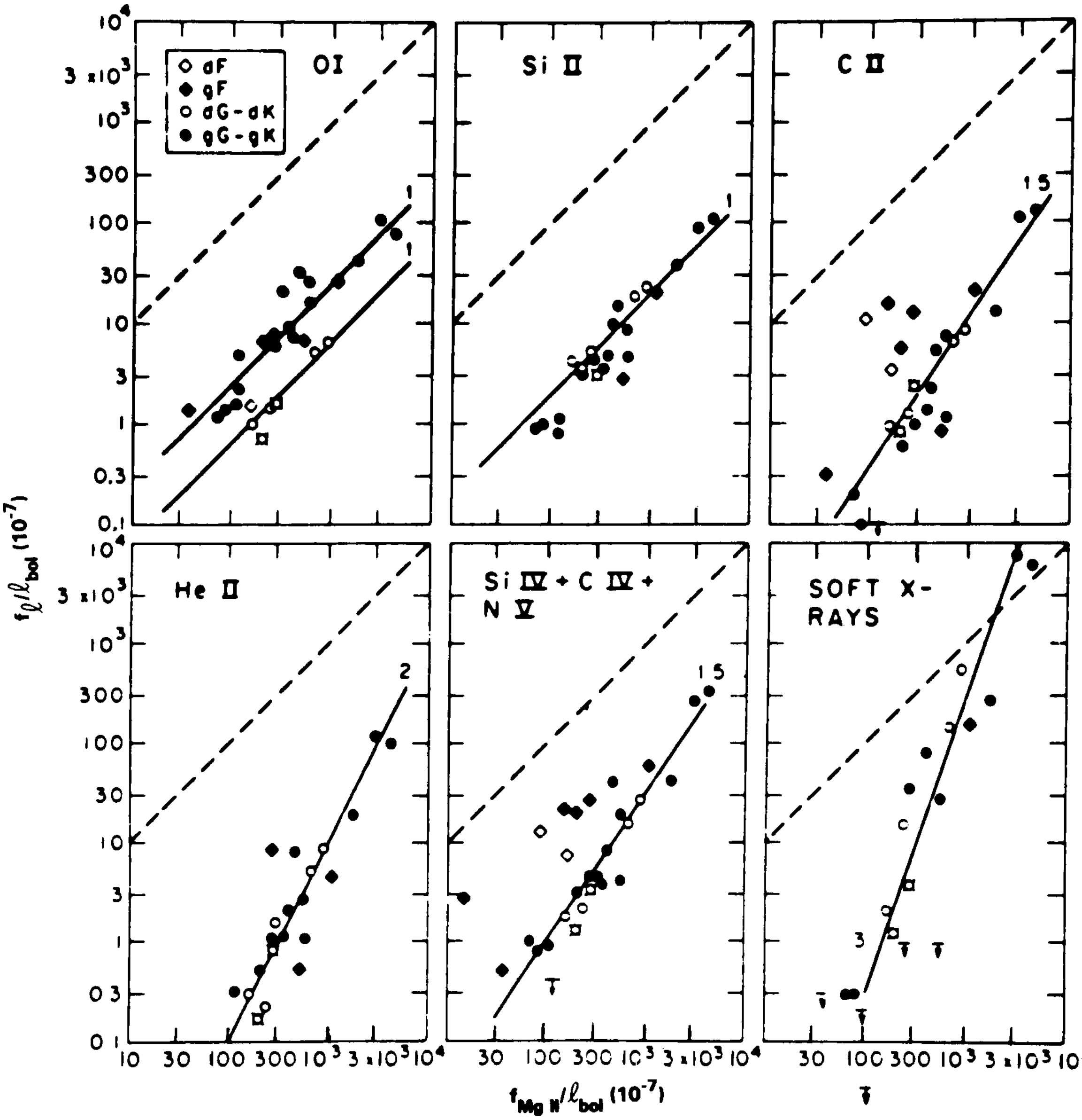


*Figure 9-11. Correlation plots showing the power-law dependence of chromospheric, transition region, and coronal fluxes from Mg II line relative flux (from Ayres et al., 1981b).*

(cf. reviews by Rosner, 1983; Belvedere, 1983), that can account for the generation and emergence of magnetic field on the stellar atmospheres (Belvedere et al., 1980; Durney et al., 1981).

6. Soft X-ray luminosities in the range $10^{26}$ to $10^{30}$ erg $s^{-1}$ have been determined for about 40 dM stars (cf. Golub, 1983; Johnson, 1983). They show a large luminosity spread and variability. Quiescent emission coronal temperatures lie in the restricted range log $T$ = 6.4 to 6.9, except for the very active stars, BY Dra and Cr Dra, whose coronal temperatures exceed $10^7$ K. Soft X-ray luminosities versus coronal temperatures are plotted in Figure 9-12 (from Serio et al., 1985).

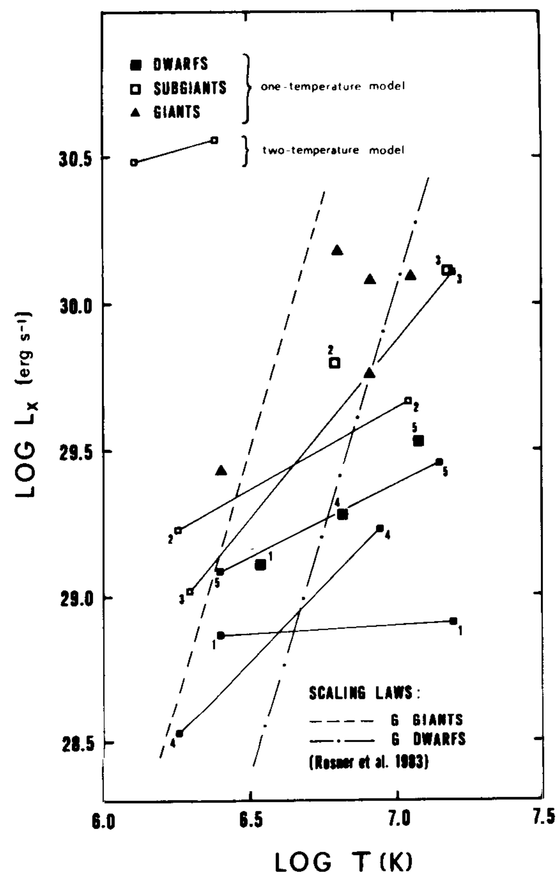


*Figure 9-12. Soft X-ray luminosity of late-type stars, including M dwarfs, versus coronal temperature from observations with the image proportional counter (IPC) of the Einstein Observatory. The IPC spectra of dwarfs and subgiants, except one subgiant, suggest two coronal components at temperatures of about 2.1 $\times$ $10^6$ and 1.3 $\times$ $10^7$ K (from Serio et al., 1985).*

It is apparent that X-ray emission is positively correlated with coronal temperature for main-sequence stars and negatively correlated with stellar surface gravity, in fairly good agreement with the Rosner et al. (1983) model for the formation and maintenance of magnetically confined hot coronal plasma. All of the X-ray spectra of cool dwarfs and subgiants, except one subgiant, in Serio et al. (1985) indicate two-temperature coronal components. The temperatures differ up to one order of magnitude and do not appear to be correlated with X-ray luminosity.

7. After several negative results and unsuccessful attempts (Altenhoff et al., 1976; Johnson and Cash, 1980), quiescent microwave emission at the 1 to 2 mJy level has been detected with very large array (VLA) from the active dMe stars chosen because of their strong X-ray coronal emission and/or other activity indicators (Gary and Linsky, 1981; Topka and Marsh, 1982; Fischer and Gibson, 1982; Gary et al., 1982; Linsky and Gary, 1983). Only upper limits were obtained for all dwarfs earlier than M except $\chi^1$ Ori (GO V). In Table 9-5, quiescent radio and X-ray data for dMe stars are presented. The detected microwave fluxes exceed by 1 to 2 orders of magnitude those predicted by assuming optically thin thermal bremsstrahlung consistent with the flat radio spectra unless implausibly large and relatively cold ($\sim 5 \times 10^6$ K) coronae are postulated, which is inconsistent with X-ray observations. Linsky and Gary (1983) conclude that gyrosynchrotron emission from a more confined nonthermal electron component is the likely emission mechanism. Occasionally, they observed both right- and left-hand circular polarization up to 50 percent.

There are now sufficient arguments suggesting that, as in the Sun, the atmospheric structures of dM and, especially, of dMe stars are controlled, even in their "quiescent" phases, by the magnetic field strength and topology (Vaiana and Rosner, 1978; Linsky, 1980a, 1983a, 1983b). The long-lasting efforts to detect those important but elusive fields are now paying their dividends; successful detection is being reported at an ever increasing rate. (See the section *Nonthermal Energy Sources of Activity and Conclusions.*)

**Table 9-5**
**X-Ray and Microwave Luminosities of Active M Dwarfs from the Einstein IPC and VLA 6-cm Fluxes, Respectively***

| Gliese (1969) No. | Star Name | Spectral Type | log $L_x$ (erg $s^{-1}$) | Ref.† | log $L_R$ (erg $s^{-1}$ $Hz^{-1}$) | Ref.† |
|---|---|---|---|---|---|---|
| 15 AB | GQ And | dM2.5e + dM4.5e | 27.1 | 1 | | |
| 65 AB | UV Cet | dM5.5e + dM5.5e | 27.3–27.6 | 1 | 13.04–13.36(B) | 2 |
| 83.1 | TX Ari | dM5e | 27.6 | | | |
| 166 C | 40 Eri C | dM4.5e | 27.8 | 1 | | |
| 206 | V 998 Ori | dM4e | 29.1 | 3 | | |
| 229 | HD 42581 | dM2.5e | 28.8 | 4 | | |
| 234 AB | V 577 Mon | dM7e | 26.9 | 4 | | |
| 268 | Ross 986 | dM7e | 27.5 | 4 | | |
| 278 C1 | YY Gem | dM1 + dM1e | 29.6 | 1 | 14.36–14.66 | 2 |
| 285 | YZ CMi | dM5e | 28.6 | 5 | | |
| 388 | AD Leo | dM4.5e | 29.0 | 4 | | |
| 406 | CN Leo | dM8e | 26.6–27.1 | 1, 4 | | |
| 412 AB | WX UMa | dM2e + dM8e | 27.5–28.5 | 4 | | |
| 477 | FI Vir | dM5 | 26.6 | 3 | | |
| 490 AB | DM + 36 2322 | dM0e + dM4e | 28.9 | 1 | | |
| 551 | V 645 Cen | dM5e | 26.6–27.4 | 4 | | |
| 612 | CR Dra | dM1.5e | 29.1 | 6 | | |
| 644 AB | V 1054 Oph | dM3.5e | 29.3 | 1 | 13.40–13.83 | 2 |
| 644 C | Wolf 630 C | dM5e | 26.4 | 4 | | |
| 719 | BY Dra | dM0e + dM2e | 29.5 | 6 | | |
| 752 AB | V 1298 Aql | dM3.5 + dM5e | 27.1 | 1 | | |
| 799 A | AT Mic | dM4.5e + dM4.5e | 29.3 | 4 | | |
| 803 | AU Mic | dM2.5e | 29.9 | 4 | | |
| 852 AB | Wolf 1561 | dM4.5 + dM5e | 29.5 | 4 | | |
| 860 AB | DO Cep | dM3 + dM4.5e | 27.4 | 1 | | |
| 866 | L 789-6 | dM7e | 26.9–27.0 | 3, 4 | | |
| 867 AB | HD 214479 | dM2e + dM4e | 29.0 | 4 | | |
| 896 AB | EQ Peg AB | dM4e + dM5.5e | 28.8 | 1 | | |
| 905 | HH And | dM6e | 26.3 | 3 | | |
| — | HD 202560 | dM0e | 27.2 | 4 | | |
| — | DM + 01 2684 | dM0e | 28.2 | 4 | | |

*When several measurements are available, the range of variability is given.
† References: 1. Vaiana et al. (1981), 2. Linsky and Gary (1983), 3. Johnson (1983), 4. Golub (1983) and references therein, 5. Kahler et al. (1982), 6. Serio et al. (1985).

Having discussed at some length the global characteristics of late-type dwarfs and, in particular, of dM-dMe stars in their quiescent phases, we can now turn our attention to their active phases. Variability on time scales from a few seconds to several months seems to be a peculiar characteristic of some dM and of all dMe stars.

This variability arises from nonstationary activity phenomena occurring in their atmospheres from atmospheric to coronal levels. Assuming the solar activity as a valid guideline, the stellar phenomena we expect to detect and study are transient atmospheric inhomogeneities (such as spots, plages, and coronal structures), flare events, and activity cycles.

### Surface Inhomogeneities in the Photosphere

Periodic, or quasi-periodic, low-amplitude wideband photometric variations are observed in several nearby K-M emission-line dwarfs and subgiants. Most of them are members of binary systems. The observed light curve shape is almost sinusoidal, so that it is widely referred to as the *photometric wave* or *distortion wave*, the latter to emphasize its distortion effects on eclipsing binary light curves. The peak-to-peak "wave" amplitudes are of the order of 0.1 magnitude and the photometric periods are typically a few days. Both the wave amplitude and period undergo striking changes. Systematic observations have shown that notable asymmetric or double-wave structures often develop, and at other times, essentially no variability is detected. Generally, after a period of apparently irregular changes, a sinusoidal wave is restored. These variations are acompanied by small ($\sim$0.01 mag), if any, *U-B* and *B-V* color changes, so that, following Kron's (1950, 1952) suggestion, they are attributed to unevenly distributed cool photospheric spots, whose visibility is modulated by the star's rotation.

The discrepancy between the spectroscopically determined 5.97599d orbital period for the double dM0 close binary, BY Dra (Bopp and Evans, 1973), and the 3.836d photometric period (Chugainov, 1966; Rodonò et al., 1983), which is identified as the active component's rotational period, has substantiated the spotted-star hypothesis or the so-called *BY Dra syndrome* (Kunkel, 1975). Typical synoptic light curves are shown in Figure 9-13. In Table 9-5, the most relevant data on the photometric wave in BY Dra stars are given. Most of the stars listed in Table 9-6 are also known UV Ceti type flare stars. (See the section *Stellar Flares.*) This makes it manifestly questionable to separate BY

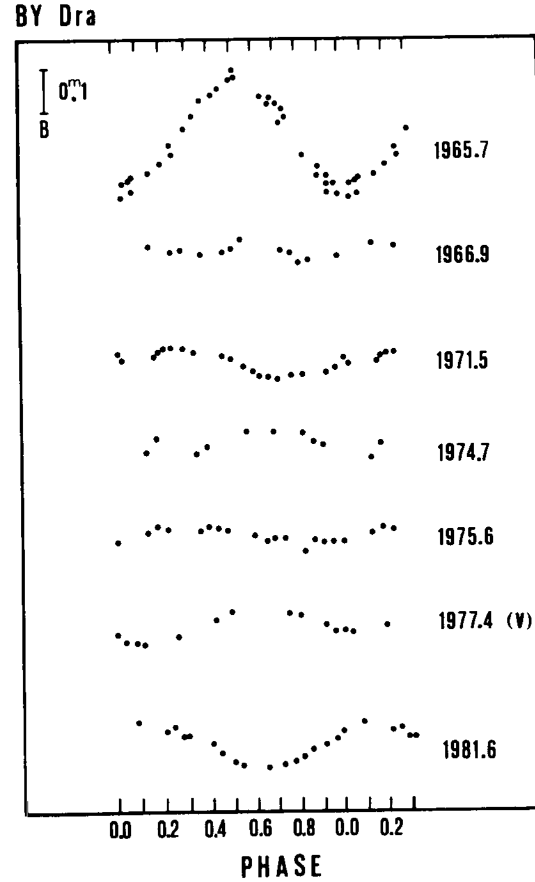


*Figure 9-13. Synoptic light curves of BY Dra from observations obtained at several places (from Rodonò, 1983). The highly variable photometric wave is attributed to surface spots, whose visibility is modulated by the star's rotation.*

## Table 9-6
## Relevant Properties of the Best Known BY Dra Type Stars
## (Most are also known UV Ceti type flare stars)

| Gliese (1969) or Woolley et al. (1970) No. | Variable Name | Catalog No. | Spectral Type | $M_V$ | $V$ | $\Delta m$ | $P_{phot}$ | Duplicity* | $P_{orb}$ | Notes† | Ref.‡ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 29.1 | FF And | BD + 34 106 | dM0e | 8.7 | 10.38 | 0.06 | 2.162 | SB 25 | 2.1730 | (a) | 1, 2 |
| 103 | CC Eri | HD 16157 | K7e V | 8.5 | 8.85 | 0.30 | 1.56 | SB 89 | 1.56145 | (a) | 3, 4 |
| 113.1 | VY Ari | HD 17433 | G9 | 5.2 | 6.87 | 0.10 | 7.85 | RV Var | | (a) | 5, 6 |
| 182 | V 1005 Ori | Yale 1121 | dM1e | 9.3 | 10.14 | 0.08 | 1.96 ? | | | (a) | 7 |
| 278 C | YY Gem | BD + 32 1582 | M1 Ve | 8.2 | 9.08 | 0.04 | 0.816 | EB | 0.81679 | (a) | 8, 9 |
| 285 | YZ CMi | Ross 882 | dM4.5e | 12.3 | 11.20 | 0.15 | 2.770 | | | (a) | 10, 21 |
| 9369 A | – | BD + 48 1958A | dM0e | 8.4 | 10.14 | 0.05 ? | – | SB 436 | 1.03382 | | 7, 11 |
| 494 | DT Vir | BD + 13 2618 | dM2e | 9.1 | 9.76 | 0.05 ? | – | | | (a) | 7 |
| 517 | EQ Vir | HD 118100 | dK5e | 7.8 | 9.36 | 0.1 | 3.96 | | | (a) | 7, 12 |
| 566 A | ξ Boo | HD 131156 | G8e V | 5.53 | 4.68 | 0.03 | 10.15 | VD | | (d) | 12 |
| 566 B | ξ Boo | HD 131156 | K4e V | 7.69 | 6.84 | – | – | VD | | (d) | 12 |
| 630.1 | CM Dra | G 225-67 | dM4e | 12.90 | 12.90 | 0.01 | 1.27 | EB | 1.26796 | | 13 |
| – | FK Ser | BD – 10 4662 | dK5e | – | 10.51 | 0.10 | 5.20 | VD | | (a) | 10 |
| 719 | BY Dra | HDE 234677 | M0 Ve | 7.4 | 8.44 | 0.25 | 3.836 | SB 695 | 5.97599 | (a) | 14, 15 |
| 799 | AT Mic | HD 196982 | dM4e | 11.1 | 10.55 | 0.07 | – | VD | | (a) | 4, 16 |
| 803 | AU Mic | HD 197481 | M0e V | 8.9 | 8.75 | 0.30 | 4.85 | SB ? | | (a) | 4, 17 |
| 815 AB | V 1396 Cyg | AC + 39 57322 | dM3e | 9.5 | 10.13 | 0.006 | – | VD | 28.25 y | (a) | 18 |
| | | | | | | | | A: SB | 3.276 | | 1, 7, 19, 20 |
| 867 A | FK Aqr | HD 214479 | dM2e | 9.3 | 9.10 | 0.06 | 4.08 ? | SB 992 | 4.08322 | (a) | 7 |
| 873 | EV Lac | BD + 43 4305 | dM4.4e | 11.5 | 10.2 | 0.03 | 4.375 | AB ? | | (a) | 21 |
| 875.1 | GT Peg | AC + 31 70565 | dM3.5e | 9.8 | 11.66 | 0.15 | 1.641 | | | (a) | 1, 10, 19 |
| 879 | TW PsA | HD 216803 | K5 Ve | 7.03 | 6.49 | 0.04 | 10.3 | SB ? | | (a) | 4, 16 |
| – | – | HD 218738 | dK2 | – | 7.98 | 0.08 | 3.0 | SB 952 | 3.03287 | (b) | 7 |
| 905 | – | Ross 248 | dM6e | 14.80 | 12.29 | 0.06 | 115 | WP ? | | | 8 |
| – | II Peg | HD 224085 | K2 V | 5.1 | 7.4 | 0.30 | 6.63 ? | SB | 6.72 | (c) | 5, 22 |
| – | – | HDE 319139 | dK5e | 7.4 | 10.4 | 0.06 | 1.7 | | | | 4 |

* Duplicity: AB = astrometric binary, EB = eclipsing binary, SB = spectroscopic binary, VD = visual binary, WP = wide pair.

† Notes: (a) flare stars, (b) B component of a wide VD with HD 218739, (c) uncertain variable-type, probably a transition prototype between RS CVn and BY Dra variables, (d) The $\Delta m$ and $P_{phot}$ data refer to the joint system.

‡ References: 1. Krzeminski (1969), 2. Bopp and Fekel (1977b) and Bopp et al. (1978), 3. Evans (1971), 4. Busko and Torres (1978), 5. Chugainov (1976a), 6. Chugainov (1976b), 7. Bopp and Espenak (1977), 8. Kron (1950), 9. Leung and Schneider (1978), 10. Chugainov (1974), 11. Bopp and Fekel (1974), 12. Ferraz Mello and Torres (1971), 13. Lacy (1977a), 14. Chugainov (1971), 15. Bopp and Evans (1973), 16. Torres and Ferraz Mello (1973), 17. Torres et al. (1972), 18. Lippincott (1975), 19. Chugainov (1973), 20. Fekel et al. (1978), 21. Pettersen (1983a), 22. Rucinski (1977), 23. Rodono et al. (1983).

Dra stars as a distinct group of variables relative to the UV Ceti type stars (Gershberg and Shakhovskaya, 1974; Rodonò, 1980).

Similar low-amplitude *photometric waves* have been found on several Pleiades dwarfs (Robinson and Kraft, 1974; van Leeuwen and Alphenaar, 1983) and on G–K subgiants, notably pre-main-sequence T Tau stars (Rydgren and Vrba, 1983) and mainly post-main-sequence components of RS CVn binaries (cf. Hall, 1981; Rodonò, 1981; Catalano, 1983).

Useful information on the physical characteristics and surface distribution of starspots can be inferred from spot modeling methods first developed by Torres and Ferraz Mello (1973). Basically, analytical light curves, which are produced by a rotating spotted-star model, are computed (cf. Bopp and Evans, 1973; Friedmann and Gurtler, 1975; Vogt, 1975, 1981a, 1981b) and compared with observations. However, due to the large number of free parameters—the inclination of the stellar rotation axis, the light level of the unspotted star, the spot location on the stellar surface, the spot extent and temperature difference with respect to the unperturbed photosphere—unique solutions are not possible unless some of the required parameters are obtained independently and accurate color variations are available (cf. Vogt's 1983 review and references therein). Although modeling a given light curve may be questionable or even meaningless, independent modeling of synoptic light curves spanning many years are of value for the purpose of investigating average characteristic and temporal behavior of spots.

Typically, spotted areas covering 10 to 40 percent of the projected stellar disk and spot temperatures cooler than the surrounding photosphere by about 400 to 1500 degrees have been inferred. Of particular value is the study of photometric period variations because it might reflect the migration of the spotted area photocenter on the surface of a differentially rotating star (Oskanian et al., 1977). The resulting lower limits obtained for binary star components are comparable to or smaller than the solar differential rotation in the 5 to 35 degree latitude range (Blanco et al., 1982; Bartolini et al., 1983; Rodonò et al., 1983; Busso et al., 1984).

This result is somewhat surprising because the huge starspots, inferred from light-curve modeling, would require powerful and efficient dynamos (i.e., higher than solar differential rotation rates). However, in addition to the circumstance that only lower limits of stellar differential rotation of binary system components have been determined, tidal coupling torques in binary systems might strongly affect the differential rotation regime of the individual components (Scharlemann, 1981, 1982; Rodonò, 1982; Catalano, 1983). This suggests that active systems experience a continuous competition between magnetohydrodynamic forces and dynamical orbital coupling, whose relative effects on stellar activity and orbital motion are at present unknown. It would be interesting to consider possible implications of this dynamical "struggle" in determining the duration and amplitude of activity cycles.

Typical characteristics of sunspots and starspots are presented in Table 9-7. A comparison of the listed parameters is valuable as long as the fundamental difference between solar and stellar observations is not overlooked: sunspot parameters are obtained from direct spatially resolved observations of active regions, whereas starspot parameters are inferred from the integrated surface properties of stellar photospheres.

Standard spot models assume either bright or dark spots to have no effect on the surrounding photosphere (i.e., no spatial redistribution of the missing flux is postulated). This is consistent with the available observations because, as noted by Hartmann and Rosner (1979), the missing flux in the large spotted area required by the observed light variations, if spatially redistributed, should produce color changes larger than those observed. Mullan (1975b) has suggested that a fraction of the missing energy in starspots could energize stellar flares. A

**Table 9-7**
**Typical Characteristics of Spots on the Sun and Active Stars**

| Parameter | Sun | Stars |
|---|---|---|
| Spectral type | G2V | K0–M5 V–IV |
| Equatorial surface velocity (km $s^{-1}$) | 2.03 | 5–40 |
| Differential rotation (rad $s^{-1}$ $degree^{-1}$) (latitude range for the Sun: 35–5 degrees) | $6.0 \times 10^{-9}$ | $< 2 \times 10^{-10}$ (RS CVn) $< 3 \times 10^{-10}$ (BY Dra) |
| Area (in unit of disk, sunspot number = 100) | $2 \times 10^{-5} - 2 \times 10^{-3}$ | 0.1 - 0.4 |
| Effective temperature (K): | | |
| Umbra | 4250 | 3500 ± 400 |
| Penumbra | 5680 | |
| Temperature difference: | | |
| Photosphere-umbra | 1800 | 600 ± 1200 |
| Photosphere-penumbra | 400 | |
| Temperature ratio: | | |
| Umbra/photosphere | 0.70 | 0.75 - 0.85 |
| Penumbra/photosphere | 0.94 | |
| Brightness ratio (V-band): | | |
| Umbra/photosphere | 0.24 | 0.30 - 0.50 |
| Penumbra/photosphere | 0.78 | |
| Variability due to rotational modulation of spots at maximum (%) | <0.03 | 10 - 40 |
| $B_0$ (kilogauss) | 1–4 | 3 - 10* |
| Lifetime of large groups (months) | < 1.5 | 0.3 - 10 |
| Spot cycle (years) | 11.04 | 5 - 60 |

*From theoretical estimates (see Mullan, 1983).

similar qualitative mechanism has been proposed by Gershberg (1983) to explain a variety of phenomena, including flare activity and the irregular light variations of T Tau stars.

Hence, in the photospheres of active late K–M emission dwarfs, strong departures from static thermal equilibrium, similar to conditions in the vicinity of a sunspot group, occur. Taking into account that the theoretical studies of the role of magnetic fields in affecting the efficiency of convective energy transport are at present inconclusive, we may conclude that, following Gershberg (1983) and Phillips and Hartmann (1978), qualitative models cannot be worked out in detail. Moreover, additional time-resolved spectroscopic and photometric data on BY Dra type variability are needed to establish firm observational constraints on theoretical models (cf. Mullan, 1983).

## Surface Inhomogeneities in the Outer Atmosphere

Pursuing the solar/stellar analogy toward the outer atmosphere, enhanced emission at chromospheric and transition region levels should occur in the so-called plages—large areas of enhanced emission that generally overlie sunspots. Their large extent is consistent with the upward divergence of magnetic field lines originating in sunspots. The most prominent chromospheric lines show variable flux correlated with both the solar cycle (Wilson, 1978; White and Livingstone, 1981) and the solar rotation phase (Bumba and Ruzickova-Topolova, 1967; Bappu and Sivaraman, 1971). The latter was detected near the minimum of the solar cycle, when the reduced number of localized plages allowed the detection of a few percent modulation of Ca II H and K line fluxes induced by the solar rotation. Oranje (1983a, 1983b) has recently shown the effect of plages on the Ca II K line intensity and profile integrated over the full solar disk (i.e., when the Sun is observed as a star). He concludes that the Ca II K variations with the solar activity cycle are largely due to plage extension and intensity variations, the chromospheric network contribution (< 8 percent) remaining unchanged.

Wilson's (1978) pioneering stellar work on Ca II H and K line fluxes has demonstrated the existence of cyclical variability on time scales close to 10 years and irregular changes on time scales from 1 day to several months on several tens of late-type main-sequence stars. A periodicity analysis of Wilson's data allowed Stimets and Giles (1980) to discover rotational modulation on 10 stars. This is a remarkable and indicative result because Wilson's sampling schedule for acquiring the data was not devised for rotational modulation studies. At present, several programs for searching for variability of stellar chromospheric lines are being carried out successfully (Baliunas and Dupree, 1979; Baliunas et al., 1981, 1983; Vaughan et al., 1981; Vaughan, 1983).

The orbital motion of binary systems offers a useful timing reference for the rotational phase of active components (i.e., for the passage of active areas across the visible hemisphere) so that it is possible to map their location and extent by monitoring the intensity of chromospheric lines (Bopp, 1974a; Ferland and Bopp, 1976; Kodaira and Ichimura, 1980, 1982). Typically, stellar plages produce variation of Ca II emission-line flux of about 10 to 30 percent. Cyclical variability is not generally observed at high flux levels, probably because the emission arises from large plages evenly distributed in longitude so that any rotational modulation is smoothed out, as at solar maximum.

The IUE is now offering an outstanding opportunity for studying stellar plages from chromospheric to transition region levels by monitoring the numerous diagnostic lines in the wavelength region 1200 to 3200 Å. (See the section *Quiescent Optical Spectra and Abundances.*) Earlier, however, marginal evidence of rotationally modulated ultraviolet emission-line fluxes was obtained by Weiler et al. (1979), Rodonò et al. (1980), Hallam and Wolff (1981), and Baliunas and Dupree (1982). Since 1980, internationally coordinated programs of simultaneous IUE and ground-based observations have clearly shown that chromospheric and transition region plages are correlated with photospheric spots (cf. Rodonò, 1983; Linsky, 1983a, and references therein). Figure 9-14 clearly shows the antiphase correlated variation of the UV emission flux in several UV chromospheric and transition region lines and of V magnitudes versus rotational phase for II Peg. Generally, the antiphase correlation of photospheric and upper atmosphere diagnostics is at best marginal for dMe stars, such as BY Dra. It is likely that microflaring activity or high plage filling factors on dMe stars make it more difficult to detect rotational modulation of plages than on K stars. Pure plage UV spectra obtained by subtracting the average quiescent spectra from those at active phases, show transition region line fluxes enhanced by a factor of 5 and chromospheric fluxes by only a factor of 2, relative to quiescent flux. The observed

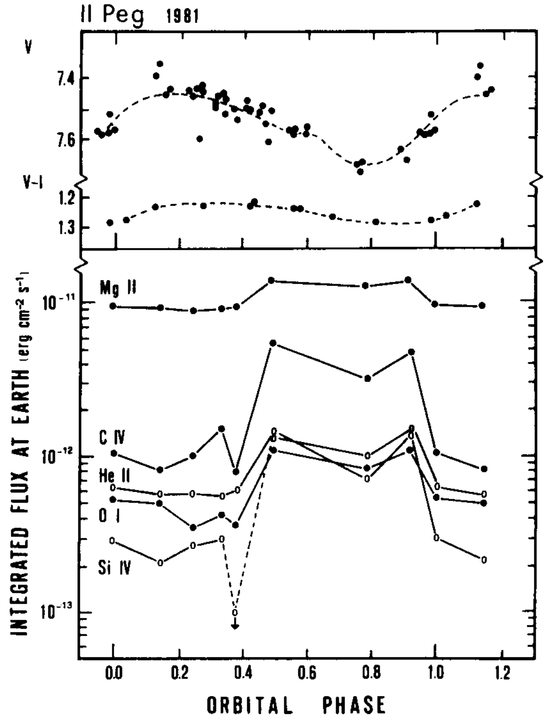


*Figure 9-14. Top: V-band photometry from ground-based observations (closed circles) and from IUE fine error sensor (FES) counts (open circles) and V–I color index. A two-spot modeling of the V light curve is also shown (dashed line). Bottom: Integrated flux in major UV lines versus photometric phases. It is evident that the photometric wave attributable to photospheric spots is anticorrelated with the line-flux variability attributable to chromopheric and transition region plages (from Rodonò et al., 1985).*

increase of line enhancement with the temperature of formation is also typical of solar plages and suggests that nonradiative energy dissipation plays an increasingly important role as temperature increases (i.e., in the outermost atmospheric layers). A quantitative comparison of solar and stellar behavior (cf. Figure 9-10) shows that, even at "quiescent" phases, the surface flux from active stars is larger than that from very active solar regions (VAR's) and becomes increasingly larger as the atmospheric level increases. Clearly, active star surfaces are covered by intense and extensive solar-like plages that affect even their "quiescent" hemisphere.

X-ray and radio observations have provided definite evidence of quiescent coronae in late-type stars and, particularly, in M dwarf flare stars and RS CVn systems. (See the section *Ultraviolet, X-Ray, and Radio Data.*) As in the Sun, highly structured coronae are expected. Again, rotational modulation of the observed X-ray flux is able to disclose such structures, as demonstrated by recent observations of YZ CMi in quiescent phases (Pettersen et al., 1980) and of the RS CVn system, AR Lac (Walter et al., 1983). Further progress requires systematic dedicated programs to be carried out with spaceborne instrumentation. Allocation of observation time for long-term programs on available X-ray satellites is not usually favored by present selection committees. Apparently, repentance does not always work in science: when Olin Wilson first applied to the U.S. National Science Foundation for a grant to carry on his pioneering and fundamental research work on stellar activity cycles, his proposal was rejected because one referee considered it not particularly motivating.

## Stellar Flares

The most prominent phenomena of stellar activity are short-lived flare events which occur in the atmosphere of K–M dwarfs and subgiants. Sudden and unpredictable enhancement of continuum and line fluxes in the optical and UV spectral domains, and of X-ray and radio emission fluxes, may occur on time scales as short as a few hundredths of seconds. Even moderately time-resolved (10 s) photometry of stellar flares indicates that, usually, complex multipeaked events, probably resulting from successive inputs of energy into the atmosphere, are observed (cf. Byrne, 1983, and references therein). Moreover, the incidence of rapidly following flares, higher than predicted by Poisson statistics (Lacy et al., 1976; Pazzani and Rodonò, 1981), suggests that sympathetic flares can occur almost simultaneously in the same

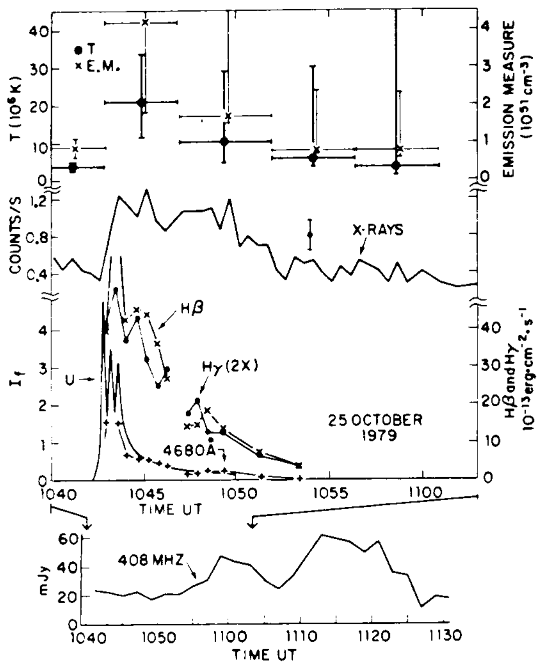


*Figure 9-15. Simultaneous optical, radio, and X-ray observations of a flare on YZ CMi (from Kahler et al., 1982).*

star (Moffett, 1972; Rodonò, 1976), like the solar flares, or in both components of a binary system (Rodonò, 1978; Fischer and Gibson, 1982). In Figure 9-15, a typical flare U-band light curve is shown, together with simultaneous X-ray and radio observations from Kahler et al. (1982). Generally, the flare color temperature is above 10000 K, so that the relative flare enhancement, normalized to the quiescent star level, increases toward shorter wavelengths because of the increasing contrast between the high-temperature flare radiation and the cool photospheric background of M dwarfs. For this reason, wideband photometry usually fails to detect flares in intrinsically bright stars due to their high photospheric background. However, in limited spectral regions or lines and at radio and X-ray wavelengths, the flare to background flux ratio is higher than in the optical region, so that flare or flare-like events have also been observed occasionally in RS CVn type K subgiants or even in earlier type stars (cf. Kunkel, 1975; Bakos, 1983), but this topic is beyond the scope of this review.

Detailed comparative studies of flares in the Sun and dM stars (Mullan, 1977; Gershberg, 1977) suggest that, also in the latter, the likely physical process underlying flaring phenomena is the storage and explosive release of magnetic energy, even though the energy involved in stellar flares is sometimes up to 2 to 3 orders of magnitude higher than in the Sun.

At present, only integrated characteristics over the entire flare region can be obtained from stellar observations. Typical parameters of stellar flares, obtained from wideband photometry of red dwarfs, are presented in Table 9-8.

Only in the optical domain have a statistically significant number of events been observed. Several statistical investigations have concluded that, with the exception of the above-mentioned possible sympathetic flares, the time intervals between flares follow Poisson statistics. Small "precursor" flares, both positive and negative, as well as overall enhancements of the quiescent flux, are observed before major flares (Rodonò et al., 1979; Cristaldi et al., 1980). However, no correlation between flare intensity and time elapsed with respect to adjacent flares is apparent (Lacy et al., 1976). The recent thorough statistical study by Shakhovskaya (1979), including 1500 flares observed mainly at the Catania, Crimea, and McDonald Observatories in 7000-hr photoelectric patrolling of 21 dMe stars, has quantitatively assessed several qualitative or preliminary results. A tendency is apparent for slow (rise time $>1$ min) and more energetic ( $>10$ erg$^{33}$) flares to occur on intrinsically brighter stars. The time-integrated energy release in U- and B-bands ranges from $10^{28}$ to a few $10^{35}$ erg. The cumulative flare frequency $\nu$ ($E_f > E_o$) (i.e., the average occurrence of flares with total energy release $E_f > E_o$) follows the linear equation $\log \tilde{\nu}\,(h^{-1}) = a - b \log E$, where $a$ depends on the star considered and $b$ ranges from 0.4 to 1.4, being systematically larger for intrinsically fainter stars and equal for the B- and U-bands. The time-averaged power due to flares decreases from a little more than $10^{29}$

Table 9-8
**Typical Parameters of Stellar Flares from Wideband Photometry**

| | | |
|---|---|---|
| Rise time (min) | 0.1 - 10* | |
| Rise/decay time (sometimes > 1) | 1. - $10^{-2}$ | |
| Log (peak power) erg $s^{-1}$ | 26.5 - 31.5 (B) | 27. - 32. (U) |
| Log (time-averaged power, $L_f$) erg $s^{-1}$ | 25.5 - 28.0 (B)* | 25.8 - 28.3 (U)* |
| Log (total energy, $E_f$) erg | 27.5 - 33.8 (B)* | 27.6 - 34.0 (U)* |
| Log ($L_f/L_{quiet\ star}$) | (-1.9) - (-3.4) (B) | |
| Mean colors at maximum: | | |
| $U-B$ | $+0.3 \pm 0.4$ | |
| $B-V$ | $-0.9 \pm 0.3$ | |
| Spectral index of occurrence rate (b) $[N(E_{\Delta t} > E) = E^{-b}\ (h^{-1})]$ | 0.4 - 1.1 (B)† | 0.3 - 1.4 (U)† |
| Time distribution | Poisson-type with strong deviation within $\Delta t < 10$ minutes. | |

*Systematically larger values for more luminous stars.
†Systematically smaller values for more luminous stars.

erg $s^{-1}$ to less than $10^{27}$ erg $s^{-1}$ for stars with absolute magnitude $M_v$ equal to 7 and 16, respectively. This implies that, in intrinsically fainter dMe stars, the time-averaged energy dissipation through flares relative to the global energy budget of the star is about 2 orders of magnitude more important than in brighter stars and accounts for about 1 percent of the energy release of the optical region.

*Optical spectroscopy of flares* (cf. Figure 9-16) indicates that there is strong intensification of the H I, Ca II, He I, and occasionally He II (4686 Å) emission lines (cf. Gershberg, 1977; Worden, 1983; Giampapa, 1983b). The equivalent width of H$\alpha$ ($\sim$2 Å) can increase by more than one order of magnitude during intense flares, and inverse Balmer decrements and large Balmer jumps (J $\simeq$ 4–6) are sometimes observed. Line broadening and red asymmetry, indicating random motion of $10^7$ to $10^8$ cm $s^{-1}$ and mass inflow at speeds of up to 1000 km $s^{-1}$, respectively, have also been observed but not in all cases (Bopp and Moffett, 1973; Worden et al., 1983). The line enhancement of the different species takes place on different time scales and can last 10 to 100 times longer than the continuum flare. The relative contribution of line emission to the continuum reaches a minimum at flare maximum (10 to 15 percent) and increases up to more than 40 percent in B-light as the flare decays. The optical flare plasma is characterized by electron densities ($N_e \approx 10^{12}$ to $10^{14}$ $cm^{-3}$) and temperatures ($T_e \approx 1.5$ to $2.0 \times 10^4$ K) ranging from solar values to much higher ones, depending on the model adopted. Typical emission measures and flare volume are $10^{52}$ $cm^{-3}$ and $10^{26}$ $cm^3$, respectively. The relative timing of line and continuum enhancements investigated by Bopp and Moffett (1973) by simultaneous photometry and time-resolved spectroscopy, and more recently by Pettersen (1983b) using narrow filters centered at hydrogen H$\alpha$ and H$\beta$ emission lines and broadband U, B, V, and R filters, indicates that the emission lines peak a few minutes after the continuum and remain enhanced for several minutes or even hours, after the continuum has decayed to its preflare level.

*UV spectra of stellar flares* on dMe stars have recently been obtained with IUE (cf. Worden, 1983; Giampapa, 1983b, and references therein). More extended and systematic observations are now being collected. However, some interesting properties have already been found: (1) a strong UV continuum—normally absent—was detected on Gliese 867A (Butler

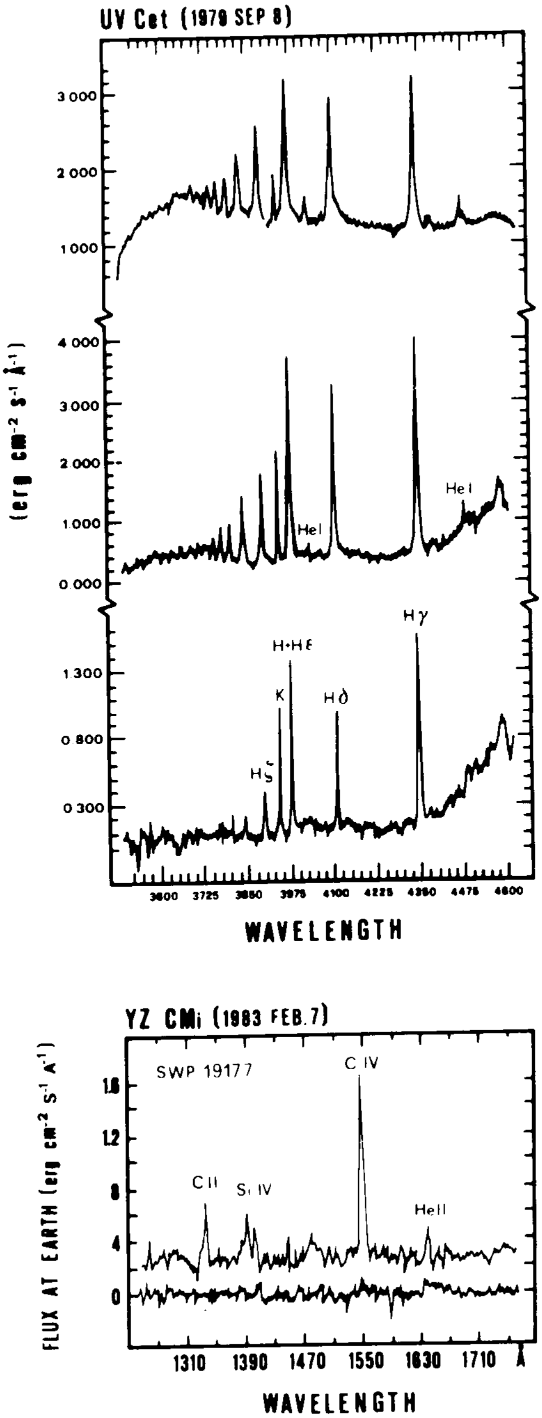


*Figure 9-16. Flare and quiescent spectra of the dMe stars in the optical (Giampapa et al., unpublished) and UV spectral domains (unpublished data from coordinated observations made by the Armagh, Catania, and Boulder groups).*

et al., 1981), YZ CMi (Figure 9-16), and Gliese 182 (unpublished data from coordinated observations by the Armagh, Boulder, and Catania groups); (2) the relative enhancement of transition region lines for flares and plages (as seen in disk-averaged fluxes) are comparable; (3) the relative emission enhancement is larger for transition region lines than for lower temperature chromospheric lines; (4) the line surface fluxes at the time of stellar flares, or from plages, can be up to more than one order of magnitude larger than those from very active regions on the Sun (Figure 9-10).

After occasional detection of *stellar X-ray flares*, several coordinated X-ray optical, and radio observations of flare and RS CVn stars have been carried out (cf. Haisch, 1983; Golub, 1983, and references therein). Comprehensive observations of a flaring event in YZ CMi (Figure 9-15) have clearly shown that the long-suspected similarity between solar and stellar flares is considerable (Kahler et al., 1982). A gradual and impulsive phase, an X-ray coronal temperature of about $10^7$ K, and the appearance of a 408-MHz burst delayed by 17 minutes from the flare onset, are similar to the corresponding typical values for type IV solar bursts. Therefore, high-energy electrons might be produced in stellar flares in the same way as in the solar flares. Due to the high sensitivity and time resolution of these Einstein observations, much better than had ever been available before, it was possible to measure simultaneously the monotonic decay of the X-ray and optical flares and the variable but ever-increasing ratio between the soft X-ray and optical fluxes ($L_x/L_c$) for most of the flare decay phase. The average ratio over the entire event was 1.5. Coupled with the observed decay time of the X-ray flux, this suggested that radiation was the predominant mechanism for cooling the coronal plasma. However, previous estimates of the $L_x/L_c$ ratio cover a wide range: from a few hundredths up to 50. Therefore, radiative cooling is not always predominant (i.e., different physical situations can develop in different flare events). Typical emission measures and densities —2 × $10^{51}$

and $3 \times 10^{11}$ cm$^{-3}$, respectively—suggest that the flare volume at coronal level is two orders of magnitude larger than that in the chromosphere.

*Radio observations of flares* on dMe stars have shown highly polarized radiation in the meter and cm wavelengths at brightness temperatures up to $10^{15}$ K in coincidence with several optical flares (Lovell, 1971; Spangler and Moffett, 1976; Melrose and Dulk, 1982; Gibson, 1983, and references therein). Basically, two types of flares have been observed: (1) impulsive events lasting from a few seconds to a few minutes, and (2) long-duration enhancement of the radio power lasting more than 10 minutes. Lang et al. (1983) have recently reported a rapid sequence of 100-percent left-hand circularly polarized spikes with rise times < 0.2 s during the gradual rise of a long-duration event on AD Leo. They derived lower limits for the linear size of the emitting region ($L > 6 \times 10^9$ cm) and of the brightness temperature ($T_B > 10^{13}$ K). These observations were explained by Lang et al. in terms of maser emission at the gyrofrequency $2.8 \times 10^6 \times H_\ell$ Hz, implying a longitudinal magnetic field $H_\ell \sim 250$ gauss. Typically, observed amplitudes for flares on nearby dwarfs range from detection limit to several tens of mJy. Although spectral indices are mainly strongly nonthermal (-2 to -10), positive spectral indices have also been reported (Gibson, 1983). The flare radio emission does not appear to be broadband, as in the quiescent phase, suggesting that the flare emission is due to coherent rather than incoherent synchrotron radiation. This is especially true for flares with brightness temperatures > $10^{12}$ K that are not compatible with incoherent emission mechanisms. The typical ratios of the optical and X-ray fluxes to the radio flux are $10^4$ to $10^5$ and < $10^3$, respectively. Bearing in mind the moderate time-coincidence of flare peaks and evolution at the various wavelengths, any conclusion would be hazardous. Actually, no systematic correlation of flare amplitudes, morphology, and time of occurrence is apparent from simultaneous multiband observations. The most extended optical-radio coverage (Spangler and Moffett, 1976) indicates only a moderate tendency for radio and optical flares to be associated within ± 10 minutes. Most likely, as suggested by Spangler and Moffett (1976), highly beamed coherent synchrotron radio emissions imply severe geometrical constraints on the detection of radio flares. Moreover, the high occurrence rate of optical flares might hinder time-coincidence studies.

## Activity Cycles

The observations of solar-type activity phenomena in late K–M dwarfs have naturally suggested that activity cycles might occur in the stars as in the Sun. Actually, as already anticipated in the section *Surface Inhomogeneities in the Photosphere*, Wilson's (1978) Ca II H and K emission-line observations have demonstrated the existence of activity cycles at the chromospheric level with time scales of 7 to 14 years. Hartmann and collaborators (cf. Hartmann, 1981, and references therein), by using the Harvard archival plate collection, have found evidence of possible cyclic photometric variations in a few well-known active dwarfs. These light variations are suggestive of starspot cycles with time scales of about 50 years. One of the red dwarfs which they studied (BD + 26° 730) is seen almost pole-on, so that its cyclic light variation can be entirely attributed to the variation of the total area covered by spots, as no rotational modulation of spot visibility can occur. For II Peg (Figure 9-17), they also found the analog of a Maunder minimum, the period of almost null solar activity, that occurred from 1645 to 1715.

Long-term cyclic suppression of convection by magnetic fields might give rise to the observed variability on time scales of the order of 10 years. Hartmann and Rosner (1979) argue that, other than spatial and spectral redistribution of the flux missing in the observed huge spotted areas, the present observations suggest that temporal redistribution of flux is more likely; the flux is temporarily stored beneath the photosphere and released when spots decay.

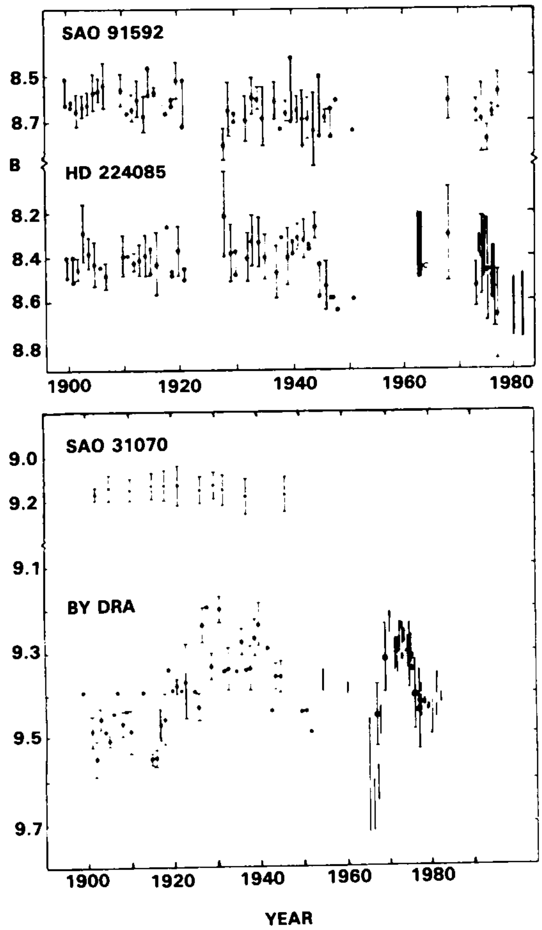


*Figure 9-17. Long-term variability of II Peg (HD 224085) and BY Dra from Harvard archival plates (Hartmann et al., 1979b; Phillips and Hartmann, 1978) and from recent photoelectric photometry (Rodonò et al., 1983, and references therein). Dots denote Harvard plates and heavy bars denote range of season variability from photoelectric photometry. BY Dra shows a clear flux modulation with a possible cycle of about 50 years. II Peg was fairly constant from 1900 to 1945, when a definite light decrease occurred. The systematic light decrease from 1970 to 1982 suggests an ever-increasing degree of spottedness. This photometric behavior suggests that II Peg has become active after a relatively quiescent interval (1900–1945), which is reminiscent of the solar Maunder minimum.*

The flare activity level on the Sun closely follows the activity cycle. Although all flare stars show significant variations of their seasonal activity level, no evidence of activity cycles has been obtained (Rodonò, 1980; Mavridis et al., 1982). Actually, the presently available data are not sufficiently extensive and systematically collected to reveal flare activity cycles. Incompleteness of data will remain serious as the short duration and random occurrence of flares make detection more dependent on observation methods and scheduling than is the case with relatively "permanent" spots. Moreover, theoretical models of activity cycles in late-type stars, particularly in M dwarfs, show that successive cycles overlap each other (Belvedere et al., 1980; Belvedere, 1984) so that any cycle-dependent variability is smoothed out. This is consistent with the decreasing number of stars showing evidence of activity cycles with advancing spectral type, although the level of activity increases, as suggested by their X-ray luminosity.

## NONTHERMAL ENERGY SOURCES OF ACTIVITY AND CONCLUSIONS

As already mentioned in the preceding sections, activity signatures and transient variability phenomena on late-type dwarfs, particularly on dMe stars, indicate that their atmospheres are controlled by energy fluxes which are nonthermal or have a nonthermal origin. In fact, the solar analogy has suggested that the whole panoply of stellar activity phenomena is directly, or at least indirectly, linked to the intensity and structure of surface magnetic fields. Consequently, the manner in which stellar magnetic fields are usually generated and strengthened has called attention to such nonthermal energy sources as *convection, velocity fields, turbulence*, and *rotation*.

Stellar structure models (e.g., Grossman et al., 1974; Cox et al., 1981) have already shown that red dwarfs later than spectral types M4–M5 are fully convective, with perhaps a tiny radiative core.

Due to the faintness of M dwarfs and the fact that their spectra are overcrowded by molecular bands, spectroscopic studies of *turbulence* and *velocity fields* are scanty. The principal aim of line-profile fittings has been that of determining the stellar-projected rotational velocity, v sin i (Anderson et al., 1977; Vogt and Fekel, 1979; Vogt et al., 1983), rather than turbulence. Cross-correlation techniques based on the comparison of observed profiles with a reference mask also appear to be very promising (Lucke and Mayor, 1980). Most of the presently available *rotational velocity* data have been obtained from the study of periodic modulation of continuum and line fluxes which are attributed to photospheric spots and chromospheric/transition region plages, respectively, whose visibility is modulated by the star rotation (cf. reviews by Rodonò, 1983; Catalano, 1983; Pettersen, 1983a; Vaughan, 1983). The rotational velocity data of BY Dra stars indicate that active stars tend to be fast rotators (v sin i > 5 km $s^{-1}$). Whether fast rotation is a sufficient condition for spot formation is still an open question. The present evidence suggests that, when both rapid rotation and deep convection occur, the consequent differential rotation is a sufficient condition for stellar activity to occur. Actually, as predicted by the so-called $\alpha$–$\omega$ dynamo (cf. Belvedere, 1983, and references therein), differential rotation generates a toroidal field ($\omega$ effect), and the twisting of field structures by the Coriolis force in a rotating star regenerates the poloidal field ($\alpha$ effect).

An indirect method of estimating stellar *differential rotation* is offered by photometric studies of active stars. Assuming starspots as tracers of stellar rotation, the variation of the "photometric wave" period as spots or the latitude of spot formation migrate on the stellar surface, together with topological data on the spot location from light-curve modeling, offers a potentially powerful method of estimating the stellar differential rotation (cf. Rodonò et al., 1983; Busso et al., 1984). Preliminary data have already been obtained and are included in Table 9-7. This approach will greatly benefit from space observations, as uninterrupted data extending over many rotations would permit, at least in principle, accurate estimations of differential rotation.

Several attempts have been made to find correlations between activity indicators such as data on Ca II, C IV, and X-ray fluxes, and rotation. (See the section *Ultraviolet, X-Ray, and Radio Data*.) Different authors have found different empirical correlations, which appear to be somewhat in conflict (Ayres and Linsky, 1980; Pallavicini et al., 1981; Ayres et al., 1981a; Catalano and Marilli, 1983; Noyes, 1983). Recently, Marilli and Catalano (1984) have rediscussed this matter by analyzing most of the available data on main-sequence stars. They were able to show that, irrespective of spectral types, the emission luminosities ($L$) in the K Ca II and C IV lines and in the soft X-ray domain are exponentially related to the stellar rotational period ($P$): $L = a\ 10^{-P/b}$, where $a$ and $b$ are numerical constants. This implies the important conclusion that the heating rates at chromospheric, transition region, and coronal levels are related. Moreover, the emission luminosities show a functional dependence on only the stellar angular velocity, as required by the $\alpha$–$\omega$ dynamo theory. Mangeney and Praderie (1983) have carried out independently a similar investigation by studying the dependence of the X-ray to convective flux ratio ($F_x/F_c$) on an effective Rossby number defined as $R_o = V_m/(\alpha\omega \ell_c)$, where $V_m$ is the maximum convective velocity, $\omega$ is the angular velocity, and $\ell_c$ is the depth of the convection zone. Again, an exponential correlation between these two parameters appears to be valid over a wide range of spectral types. However, for late F- to M-type dwarfs, the result by Mangeney and Praderie (1983) indicates a dependence also on the depth of convection zone (i.e., on the spectral type), in contrast to Marilli and Catalano's (1984) result. Only more extended and statistically complete data sets, together with progress on nonlinear $\alpha$–$\omega$ dynamo theory calculations, can throw light on this matter.

Until recently, the missing piece of the increasingly coherent scenario of stellar activity was the detection of surface *magnetic fields.* Robinson (1980) has employed the technique of comparing the profiles of magnetic sensitive and insensitive lines to measure the excess broadening due to the components of the Zeeman triplet originating in a magnetic field. The Robinson technique also allows us to estimate the ratio of magnetic-to-nonmagnetic areas (filling factor) from the relative enhancement of the central component with respect to the outer components (Figure 9-18). About 20 G-K dwarfs have detected magnetic fields in the range 500 to 3000 gauss with area filling factors ranging from 20 to 80 percent (Marcy, 1983; Giampapa and Worden, 1983). These data imply magnetic fluxes 2 to 3 orders of magnitude greater than the solar flux, which is consistent with the huge activity phenomena observed in these stars. Although the data are meager, they suggest some interesting qualitative conclusions: (1) the ratio of soft X-ray flux to bolometric flux increases as the photospheric magnetic area coverage increases (i.e., the photospheric magnetic fields control the stellar atmospheres up to coronal level); (2) the magnetic field flux increases toward later spectral types and with increasing rotational velocity, in qualitative agreement with the two basic requirements of the $\alpha$–$\omega$ dynamo theory (Belvedere et al., 1981).

An additional indirect evidence that active star atmospheres are controlled by magnetic structures has recently been presented by Musielak and Bielicz (1982, 1983). From theoretical models of intense magnetic flux tubes (Bielicz and Musielak, 1982), they have shown that in active stars the atmospheric level of temperature minimum rises and the average magnetic field is higher than in nonactive stars. These models were used to compute the Ca II K line width ($W_0$) for both types of stars for the purpose of interpreting the corrected Wilson-Bappu effect, which takes into account the dependence of $W_0$ on the intensity of the K line itself (Glebocki and Stawikowski, 1980). As already suggested by Zwaan (1977), the line width $W_0$ is a powerful quantitative diagnostic of the average properties of the discrete magnetic flux tubes which permeate the atmospheres of active stars.

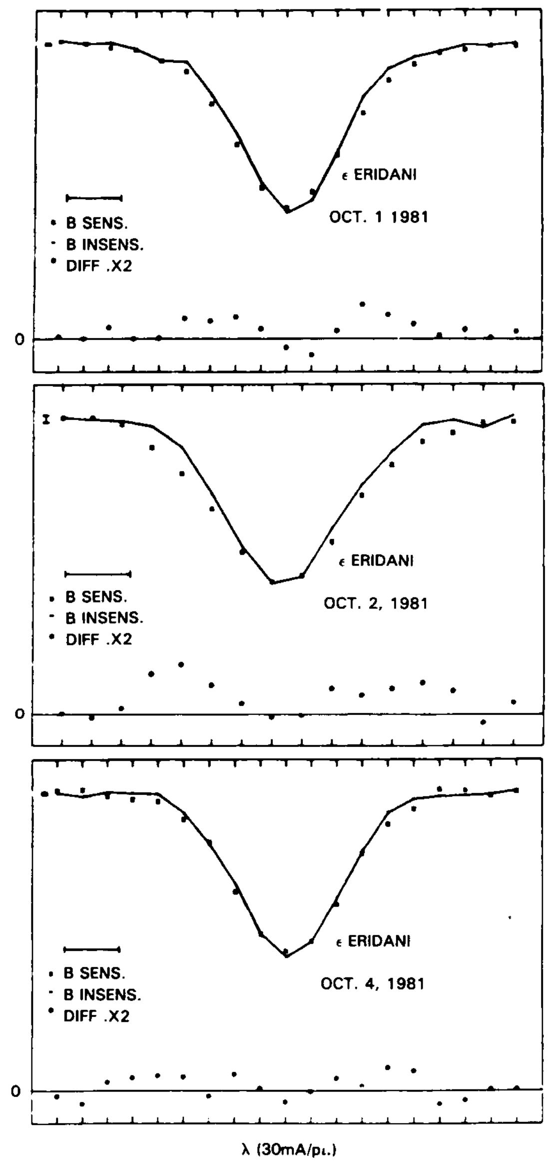


*Figure 9-18. Comparison between the observed line profiles of the Zeeman sensitive line (6173.34 Å) and the insensitive line (6240.65 Å) of Fe I, represented by the dots and the continuous line, respectively. The bottom curve on each panel shows the difference between the two profiles, multiplied by 2. Observed changes in the difference profile suggest that the magnetic field on ε Eridanii changes on a time scale of 1 day (from Marcy, 1983).*

The observations reviewed in this chapter clearly indicate that a basic solar-type scenario underlies the nonthermal activity phenomena which occur in the atmospheres of late-type main-sequence stars, particularly late K–M emission-line dwarfs. This returns us to the fundamental concept presented in the introductory section on the scientific value of the two-way street connecting solar and stellar research in the study of nonthermal activity phenomena occurring in their atmospheres.


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